ABOVEGROUND CARBON STOCK ESTIMATION OF AGROFORESTRY SYSTEMS IN BALUNG PLANTATION, TAWAU, SABAH USING AIRBORNE LIDAR DATA

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DEDICATION

I dedicate this thesis to my Late Father, Mr. Jimpony @ James Jimponey bin Mosikul (1946 – 2006), who throughout his lifetime etched in the walls of my heart the importance of education.

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ABSTRACT

Agroforestry systems have a promising potential in climate change mitigation by storing carbon in the multistorey planted trees and crops. However, there has been very few research on quantifying aboveground carbon (AGC) stock of agroforestry systems in Malaysia. Thus, this study was conducted in Balung Plantation, Tawau, Sabah, with the aims to determine the AGC stock potential and also to evaluate the performance of LiDAR data in assisting AGC stock estimation of the agroforestry systems. Three types of teak-based agroforestry systems combination were studied mainly polyculture system 1 (teak + agarwood + snake fruit), polyculture system 2 (teak + coffee) and polyculture system 3 (teak + agarwood). In addition, teak monoculture plantation and natural forest reserve (Tawau Hill FR) was treated as controls. A total of 20 square plots (50 m × 50 m) was established in the agroforestry systems while 3 square plots (50 m × 50 m) was established in the teak monoculture plantation and 6 square plots (30 m × 30 m) in the natural forest reserve. Aboveground biomass (AGB) was calculated from the field measured DBH and height using allometric equations and converted into AGC stock using a conversion factor of 0.50. The results showed that the accumulation of AGC stock is in the following order: natural forest reserve (213.84 t C/ha) > polyculture system 3 (69.94 t C/ha) > polyculture system 2 (37.75 t C/ha) > polyculture system 1 (37.34 t C/ha) > teak monoculture plantation (34.53 t C/ha). The findings have demonstrated that the agroforestry systems are capable to store about a quarter percent of the total AGC stock of a natural forest reserve which is relatively better than the monoculture plantation. For the AGC estimation using airborne LiDAR data, two estimation approaches were used (Approach 1: AGC estimation based on the layering of species-specific AGC models developed through vertical canopy stratification; and Approach 2: AGC modelling through the combination of all sample plots). LiDAR metrics such as height metrics, cover density metrics, strata density metrics and canopy cover percentage metrics was extracted from the LiDAR point clouds data (all returns) and regressed with field AGC to establish the AGC estimation models. Through the layering of the best AGC estimation models for teak trees (Adj-R^2_{cv}= 0.92, %$RMSE_{cv}$ = 12.65 %), agarwood trees (*2 outlier removed; Adj-R^2_{cv}= 0.86, %$RMSE_{cv}$ = 44.21 %) and understorey crops (Adj-R^2_{cv}= 0.40, %$RMSE_{cv}$ = 15.88 %), the approach 1 method were able to explain 81 % (%$RMSE_{cv}$ = 17.65 %) of the AGC variance in the agroforestry systems. Through linear regression model without transformation, the approach 2 method has improved the estimation by 3 % with AGC estimation performance of 84 % (%$RMSE_{cv}$ = 13.45 %). Overall, this study showed that the teak trees have a great potential in transforming a low biomass land cover into a carbon-rich tree based agroforestry systems, with the capability to store more than 60 % of the total AGC stock in the agroforestry systems. This study also demonstrated that airborne LiDAR data was capable in estimating AGC of agroforestry systems at the plot level with high accuracy.

ABSTRAK

PENGANGGARAN STOK SIMPANAN KARBON ATAS TANAH DI DALAM SISTEM PERHUTANI DI LADANG BALUNG, TAWAU, SABAH MENGGUNAKAN DATA LIDAR BAWAAN UDARA

*Sistem perhutani mempunyai potensi yang besar dalam mitigasi perubahan iklim dengan menyimpan karbon di dalam pokok dan tanaman pertanian yang ditanam secara berbilang tingkat. Walaubagaimanapun, tidak banyak kajian yang dijalankan mengenai simpanan stok karbon atas tanah (AGC) di dalam sistem perhutani di Malaysia. Oleh itu, kajian ini telah dijalankan di Balung, Tawau, Sabah, dengan tujuan untuk menilai keupayaan penyimpanan stok AGC dan juga menilai keupayaan data LiDAR dalam menganggar stok AGC sistem perhutani. Tiga jenis kombinasi sistem perhutani berasaskan jati telah dikaji iaitu polikultur sistem 1 (jati + gaharu + salak), polikultur sistem 2 (jati + kopi) dan polikultur sistem 3 (jati + gaharu). Selain itu, ladang jati monokultur serta hutan simpan semulajadi (Hutan Simpan Taman Bukit Tawau) dijadikan sebagai kawalan. Sebanyak 20 plot segi empat tepat (50 m × 50 m) telah dibuat di sistem perhutani manakala 3 plot segi empat tepat (50 m × 50 m) dibuat di ladang jati monokultur dan 6 plot segi empat tepat (30 m × 30 m) di hutan simpan semulajadi. Biojisim atas tanah (AGB) dikira menggunakan rumus alometri berdasarkan ukuran DBH dan tinggi yang direkod di lapangan dan ditukar kepada stok AGC menggunakan faktor penukaran 0.50. Keputusan menunjukkan pengumpulan stok AGC adalah dalam turutan berikut: hutan simpan semulajadi (213.84 t C/ha) > polikultur sistem 3 (69.94 t C/ha) > polikultur sistem 2 (37.75 t C/ha) > polikultur sistem 1 (37.34 t C/ha) > ladang jati monokultur (34.53 t C/ha). Hasil kajian menunjukkan sistem perhutani mampu menyimpan sebanyak satu per empat peratus daripada jumlah stok AGC yang terdapat di dalam hutan simpan semulajadi yang secara relatifnya adalah lebih baik berbanding ladang monokultur. Bagi penganggaran simpanan stok AGC menggunakan data LiDAR, dua jenis pendekatan telah digunakan (Pendekatan 1: penganggaran stok AGC berdasarkan pelapisan model AGC spesis-spesifik yang dihasilkan melalui stratifikasi kanopi secara menegak; dan Pendekatan 2: pemodelan AGC melalui kombinasi kesemua sampel plot lapangan). Metrik LiDAR seperti metrik ketinggian, metrik kepadatan litupan, metrik kepadatan strata serta metrik peratusan litupan diekstrak daripada data LiDAR (kesemua pantulan) dan diregresikan dengan data AGC lapangan bagi menghasilkan model anggaran AGC. Melalui pelapisan model AGC yang terbaik bagi pokok jati ($Adj\text{-}R^2_{cv}$= 0.92, $\%RMSE_{cv}$ = 12.65 %), pokok gaharu (*2 outlier dikeluarkan; $Adj\text{-}R^2_{cv}$= 0.86, $\%RMSE_{cv}$ = 44.21 %) dan tanaman pertanian di kanopi bawah ($Adj\text{-}R^2_{cv}$= 0.40, $\%RMSE_{cv}$ = 15.88 %), kaedah pendekatan 1 mampu menjelaskan sebanyak 81 % ($\%RMSE_{cv}$ = 17.65 %) varians stok AGC di dalam sistem perhutani. Menggunakan model regresi linear tanpa transformasi, kaedah pendekatan 2 telah meningkatkan kebolehanggaran sebanyak 3 % dengan prestasi penganggaran stok AGC mencapai 84 % ($\%RMSE_{cv}$ = 13.45 %). Secara keseluruhannya, kajian ini menunjukkan bahawa pokok jati mempunyai potensi besar dalam mengubah kawasan berbiojisim rendah kepada sistem perhutani berasaskan pokok yang kaya dengan karbon, dengan keupayaan untuk menyimpan sebanyak 60 % daripada jumlah keseluruhan stok AGC di dalam sistem perhutani. Kajian ini juga telah menunjukkan bahawa LiDAR bawaan udara mampu menganggarkan AGC sistem perhutani pada peringkat plot dengan ketepatan yang tinggi.*

TABLE OF CONTENTS

CHAPTER 1: INTRODUCTION

CHAPTER 2: LITERATURE REVIEW

CHAPTER 3: METHODOLOGY

CHAPTER 4: RESULTS

CHAPTER 5: DISCUSSION

CHAPTER 6: CONCLUSION

LIST OF TABLES

LIST OF FIGURES

LIST OF EQUATIONS

LIST OF ABBREVIATIONS

ABA	-	Area Based Approach
AGB	-	Aboveground Biomass
AGC	-	Aboveground Carbon
AIC	-	Akaike Information Criterion
AMSL	-	Above Mean Sea Level
ASPRS	-	American Society of Photogrammetry and Remote Sensing
AVHRR	-	Advance Very High Resolution Radiometer
CBD	-	Convention on Biological Diversity
CDM	-	Canopy Density Metrics
CDM*	-	Clean Development Mechanism
CERs	-	Certified Emission Reductions
CHM	-	Canopy Height Model
DBH	-	Diameter at Breast Height
DGPS	-	Differential Global Positioning System
DTM	-	Digital Terrain Model
FAO	-	Food and Agriculture Organization of the United Nations
FR	-	Forest reserve
GHGs	-	Greenhouse gases
GNSS	-	Global Navigation Satellite System
GPS	-	Global Positioning System
ICRAF	-	International Centre for Research in Agroforestry
IMU	-	Inertial Measurement Unit
IPCC	-	Intergovernmental Panel on Climate Change
ITA	-	Individual Tree Approach
JAPAN	-	Japan Association of Precise Survey and Applied Tecnology
JUPEM	-	Malaysian department of Survey and Mapping
LAI	-	Leaf Area Index
LiDAR	-	Light Detection and Ranging
LMS	-	LiDAR Mapping Suite

LOOCV - Leave One Out Cross Validation
NASA - National Aeronautics and Space Administration
NRC - National Research Council
NRD - Normalize Relative Strata Density
ORD - Overall Relative Strata Density
PRF - Point repetitive frequency
REDD+ - Reducing Emissions from Deforestation and Forest Degradation in Developing Countries, and the Role of Conservation, Sustainable Management of Forests, and Enhancement of Forest Carbon Stocks in Developing Countries
RMS - Root Mean Squared
RMSE - Root Mean Squared Error
RMSE$_{cv}$ - Root Mean Squared Error (Cross Validated)
TNAU - Tamil Nadhu Agriculture University
UCS - Union of Concerned Scientist
UNFCC - United Nations Framework Convention on Climate Change
UNH - University of New Hampshire
USDA - United States Department of Agriculture
UTM - Universal Transverse Mercator
VIF - Variance Inflation Factor
WGS - World Geodetic System

LIST OF SYMBOLS

10^6 - Ten (10) million
3D - Three Dimensional
- - Minus/dash
% - Percentage
.las - LiDAR data exchange file
′ - Minute
″ - Second
+ - Plus/positive
< - Less Than
= - Equal to
Adj-R^2 - Adjusted Coefficient of Determination
Adj-R^2_{cv} - Adjusted Coefficient of Determination (Cross Validated)
B - Coefficient
C - Carbon
CC % - Canopy Cover Percentage
cm - Centimeter
CO_2 - Carbon Dioxide gas
D - Diameter
dz - Delta Elevation
E - East
e.g. - *exempli gratia* (for example)
Exp - Exponential
Gt - Gigatonne
H - Height
ha - Hectare
ha^{-1} - Per hectare
h_{cv} - LiDAR height coefficient of variation
h_{max} - LiDAR maximum percentile height
h_{mean} - LiDAR mean percentile height

Hz - Hertz

i.e. - *id est* (in other words/that is)

kHz - Kilohertz

km - Kilometer

km^2 - Kilometer square

kts - Knots

Ln - Natural Logarithm

LR$_{wt}$ - Linear regression without transformation

LR$_{wLn-t}$ - Linear regression with Ln-transformation

m - Meter

M - Million

Mg - Megagram

mm - Millimeter

Mt - Metric tonne

N - North

n - Number of samples/plots/observation

No. - Number

n.a. - Not Available

° - Degree

Obs. - Observation

°C - Degree Celcius

PPM^2 - Point per square meter

R^2 - Coefficient of determination

R$^2_{cv}$ - Coefficient of determination (Cross Validated)

S - South

S.D. - Standard deviation

S.E. - Standard Error

Sig. - Significant

t - Tonne, T-test

t C/ha - Tonne Carbon per hectare

W - West

× - Multiply

Σ - Sum of
- Total of

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Study Background

Carbon is the fourth most abundant element in the universe and serves as a common element for all living organisms. Similar to the nitrogen and water cycle, the carbon cycle is important for sustaining life. Carbon sequestration refers to the carbon capture and long term storage of atmospheric carbon dioxide (CO_2) gas. On earth, carbon is sequestered and stored in the terrestrial and marine ecosystems whereas a small portion of carbon constitutes within the earth's atmosphere. It was estimated that about 2500 Gt carbon are stored in the terrestrial ecosystems compared to 750 Gt carbon within the atmosphere (Convention on Biological Diversity [CBD], 2009). Forest ecosystems such as the primary tropical rainforest, sequesters the most carbon of any terrestrial ecosystems and it is considered as the main natural break in mitigating climate change (Gibbs *et al.,* 2007). Forest sequesters carbon dioxide from the atmosphere through photosynthesis process and acts as a carbon sink in which it prevents the carbon from being released back to the atmosphere by storing it up for good. At present, forest covers approximately 30.6 % of the total global land area and stores a massive amount of carbon (289 Gt C) in their biomass alone (MacDicken *et al.*, 2016; Food and Agriculture Organization of the United Nations [FAO], 2010).

However, due to the extensive needs of area for urbanization, community settlement, establishment of plantation, agricultural areas and many other activities, forested land clearing has become highly inevitable. Over the past decades, large areas of forest have been destroyed, cleared, overharvested or burned, and converted to non-forest use. A considerable extent of forest areas was reported to already been lost, especially in less developed and developing countries all over the world (Kumar and Nair, 2011). The conversion of forest areas to other land uses was identified as the source of carbon emission. In 2016, Food and Agriculture Organization of the United Nations (FAO) have reported that the annual rate of deforestation was 0.08 % during the period of 2010 to 2015 (MacDicken *et al.*, 2016). Deforestation activities have been widely accepted as one of the major contributors to global climate change which is the most serious environmental issues affecting the environment and also human lives (Hairiah *et al.*, 2001).

Deforestation activities increase the concentration of greenhouse gases (GHGs) in the atmosphere as the deforested landscapes fails to capture and stores CO_2 which is the main GHGs components. According to Intergovernmental Panel on Climate Change, IPCC (2013), CO_2 has contributed more than any other driver to climate change between 1750 and 2011 as a result of human anthropogenic activities, as well as land use change. Approximately 20 % of all carbon emissions were attributed from deforestation and forest degradation. High concentrations of CO_2 within the atmosphere are associated with global warming, that is the increase in the earth's temperature due to the fact that CO_2 is a heat-trapping gas. CO_2 remains in the atmosphere longer than other major heat-trapping gases emitted in which, after a pulse of CO_2 is emitted into the atmosphere, 40 % will remain for 100 years and 20 % will reside for 1000 years, while the final 10 % will take 10,000 years to turn over (Union of Concerned Scientist [UCS], 2017). This literally means that the heat-trapping emissions that were released at present are setting the future climate. According to the National Aeronautics and Space Administration, NASA (2016), their ongoing temperature analysis shows that the average annual global temperature has increased about 0.8 °C since 1880. Although the figures may seem small, but the effect on the environment are highly noticeable. The rising of sea levels, melting of glacier in the north and south poles, frequent flooding and drought, stronger typhoon, are among the negative effects of the increasing earth's temperature (Cowie, 2007).

Climate change has threatened the economic system, livelihoods and the availability of natural resources in several regions of the world (Hansen *et al.*, 2006), and it has become a crucial challenge in adaptating to the unavoidable climate change. As a way of mitigating climate change, it is important to reduce the concentration of CO_2 within the atmosphere and putting it into an equilibrium state. However, stabilization of CO_2 levels in the atmosphere takes decades and can only be achieved by reducing CO_2 emissions and increase the carbon pool areas. Indeed, there were strategies established to restore major degraded and deforested land into a rich carbon pool system. Afforestation, reforestation and deforestation avoidance strategies have been carried out as a way of mitigating climate change (Reyer *et al.,* 2009). These actions can contribute in reducing of up to 25 % of atmospheric CO_2 by 2050 by reducing emissions, increase CO_2 removals through sinks at low costs and have synergies with adaptation and sustainable development (Niles *et al.*, 2002; Barker *et al.,* 2009). Massive reforestation would be the best solution proposed in stabilizing the concentration of CO_2 in the atmosphere. In spite of that, it is facing difficulties in implementation considering the current rates of deforestation in the tropics and the high demands on the use of large area especially for agricultural purposes. Halting deforestation remains a challenge largely due to unsustainable agriculture practices that degrades natural ecosystems. It was reported that 90 % of deforestation was driven by agriculture activities in which 60 % are attributed from the extension of agro-industrial farming (i.e. oil palm and rubber plantations) while the remaining 30 % are caused by small scale and subsistence farmers (Laporte *et al.*, 2007).

Realizing the important roles of trees to capture and store carbon in vegetation, soils and biomass products (Malhi *et al.*, 2008), and understanding the inevitability to prevent the loss of forest ecosystems, there were needs in transforming low biomass land uses of agricultural land to a carbon-rich tree based agroforestry (Kumar and Nair, 2011). In the agricultural sector, many plantation areas practices monoculture (single species) planting while short-term annual crops is cultivated in the agricultural farm. It may carry out some carbon sink functions, but at a very minimal rate. Agroforestry systems has a great potential in carbon storing primarily in agricultural dominated landscapes compared to monoculture plantation and agricultural crop farm (Nair *et al.*, 2009). Agroforestry systems has been found to have a significant role for carbon storage and sequestration, which provides an aided solution, apart from rehabilitation and restoration of forest areas, for climate change mitigation strategies (Morgan *et al.*, 2010). Agroforestry