NON-DESTRUCTIVE INDIVIDUAL TREE ABOVEGROUND BIOMASS ESTIMATION IN TROPICAL RAINFOREST USING TERRESTRIAL LASER SCANNER

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Untuk Mama Abah…
Dan yang teristimewa, Lina Farhana…

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ABSTRACT

Recent methods for detailed and accurate biomass and carbon stock estimation are driven by advances in remote sensing technology. However, this method heavily relies on the availability of species and area dependent allometric equations, which has been long based on the destructive method. This study introduces a non-destructive laser-based approach for individual tree aboveground biomass estimation by developing a semi-automatic approach of individual tree measurement using the collected point cloud. Biomass of individual trees was derived from tree parameters estimated using terrestrial laser scanner (TLS) data and assessed with field collected data. This study also improvised available allometric models for aboveground biomass estimation based on tree species and individual tree properties obtained from TLS. Point cloud for this study were generated using TLS (Riegl-VZ400) representing 118 random trees from 39 plots established in Royal Belum forest reserve in the state of Perak, Malaysia. Individual tree census was carried out to collect detailed primary tree attributes such as diameter at breast height and tree height. The scanning process using TLS was done to acquire point cloud in multiple positions to ensure good visibility of individual tree. Detailed tree measurement was carried out on the point cloud generated from TLS and the results were compared with the ground collected data. The volume of tree trunk is estimated based on cylinder model fitting on point cloud. The biomass of tree trunk is calculated by multiplying the volume with the species dependent wood density values. The biomass of branches and leaves were estimated based on the same concept and the point cloud were fitted with convex-hull approach. The estimated biomass from TLS was compared with the biomass estimated using existing allometric equations. Measurements of individual tree attributes from the point cloud produced diameter at breast height estimates with of 0.06 cm root mean square error with overestimation of 0.03cm. The root mean square error value for tree height and crown base height estimates is 7.10m and 4.31m with underestimation of 3.07m and 1.05m respectively. In general, the estimated biomass of tree trunk shows strong correlation with biomass value obtained from the allometric equation with *r* value of 0.97. The estimated branch and leaves biomass show poor relationship with biomass estimated using existing allometric equations with *r* value of -0.12 and 0.24 respectively. The findings on species-specific non-destructive laser-based approach suggests similar correlation pattern observed for biomass of stem, branches, leaves and total aboveground biomass of all tree species with mean of *r* value of 0.92, -0.12, 0.24 and 0.91 respectively. The proposed methodology and results obtained in this study allow generation of species-specific allometric equations in which suitable with LiDAR-derived variables for individual trees biomass estimation which is a promising alternative approach to the destructive method.

ABSTRAK

Kaedah terkini bagi penganggaran biojisim dan stok karbon secara terperinci dan tepat telah didorong oleh kemajuan dalam teknologi penderiaan jauh. Walau bagaimanapun, kaedah ini banyak bergantung kepada kebolehsediaan persamaan allometrik yang bergantung kepada ketersediaan spesis dan kawasan, yang telah lama digunakan berdasarkan kaedah memusnah. Kajian ini memperkenalkan pendekatan tidak memusnah berasaskan laser untuk penganggaran biojisim atas tanah bagi setiap pokok dengan menghasilkan kaedah penganggaran pokok individu secara separa automatik menggunakan titik awan. Biojisim bagi setiap pokok telah diperolehi menggunakan penganggaran pemboleh ubah pokok yang dianggarkan menggunakan pengimbas laser darat (TLS) dan dinilai menggunakan data lapangan. Kajian ini juga menambahbaik model allometrik sedia ada untuk penganggaran biojisim atas tanah berdasarkan spesis tertentu dan ciri-ciri pokok individu yang diperoleh daripada TLS. Titik awan untuk kajian ini telah dijana menggunakan TLS (Riegl-VZ400) yang mewakili 118 pokok secara rawak daripada 39 plot di hutan simpan Royal Belum, Perak, Malaysia. Bancian pokok secara individu telah dilakukan untuk mengumpul ciri-ciri utama pokok iaitu garis pusat pada paras dada dan ketinggian pokok secara terperinci. Proses imbasan menggunakan TLS untuk mendapatkan titik awan telah dilakukan pada beberapa posisi untuk memastikan penglihatan yang baik terhadap setiap pokok. Pengukuran pokok secara terperinci dijalankan pada titik awan yang dijana oleh TLS dan hasilnya dibandingkan dengan data lapangan. Isipadu batang pokok dianggar berdasarkan pemasangan model silinder pada titik awan. Biojisim batang pokok dikira dengan mendarabkan isipadu dengan ketumpatan kayu yang bergantung kepada spesis. Anggaran biojisim dahan dan daun adalah berdasarkan konsep yang sama dan titik awan dipasang menggunakan pendekatan hul cembung. Biojisim yang dianggar menggunakan data TLS telah dibandingkan dengan nilai anggaran menggunakan persamaan allometrik yang sedia ada. Pengukuran sifat-sifat pokok daripada titik awan telah memberi anggaran garis pusat pada paras dada dengan nilai punca purata ralat kuasa dua bersamaan 0.06cm dan dengan lebihan anggaran sebanyak 0.03cm. Nilai punca purata ralat kuasa dua untuk anggaran ketinggian pokok dan ketinggian dasar mahkota adalah 7.10m dan 4.31m dengan bawah anggaran 3.07m dan 1.05m. Secara umumnya, anggaran biojisim batang pokok menunjukkan korelasi yang kukuh terhadap nilai biojisim daripada persamaan allometrik dengan nilai r bersamaan 0.97. Anggaran biojisim dahan dan daun menunjukkan hubungkait yang lemah terhadap nilai biojisim persamaan allometrik dengan nilai r bersamaan -0.12 dan 0.24. Dapatan dari kaedah pendekatan laser tidak memusnah terhadap spesis tertentu menunjukkan corak hasil korelasi yang sama terhadap biojisim batang, dahan, daun dan keseluruhan biojisim atas tanah bagi setiap spesis dengan nilai purata r bersamaan 0.92, -0.12, 0.24 dan 0.91. Kaedah yang dicadang dan hasil daripada kajian ini membolehkan persamaan allometrik spesis khusus yang bersesuaian dengan pemboleh ubah daripada LiDAR digunakan untuk penganggaran biojisim pokok-pokok dan menjadi pendekatan alternatif kepada kaedah memusnah.

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LIST OF ABBREVIATIONS

FAO	-	Food and Agriculture Organization
REDD	-	Reducing Emissions from Deforestation and Forest Degradation
UNFCCC	-	United Nation Framework Convention on Climate Change
TLS	-	Terrestrial Laser Scanning
ALS	-	Airborne Laser Scanning
UAV	-	Unmanned Aerial Vehicle
DSM	-	Digital Surface Model
DTM	-	Digital Terrain Model
CHM	-	Canopy Height Model
DGPS	-	Differential Global Positioning System
IMU	-	Inertial Measurement Unit
GPS	-	Global Positioning System
DBH	-	Diameter at Breast Height
CBH	-	Crown Base Height
Ws	-	Weight of Stem
Wb	-	Weight of Branches
Wl	-	Weight of Leaves
TAGB	-	Total Aboveground Biomass
RMSE	-	Root Mean Square Error
MAE	-	Mean Absolute Error

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CHAPTER 1

INTRODUCTION

1.1 Background of study

Forests area occupies thirty percent of terrestrial land surface with high biological diversity in which they shelter over two-thirds of known terrestrial species (WWF-Malaysia, 2013). It is hard to define a forest in few words in which when asked of it, most people will straightaway be thinking of trees. Forest is a whole lot more than just a large area full of trees, they are comprise of complex ecosystem of trees, animals and microorganism in which they help by providing habitats and food to maintain biodiversity (FAO, 2013). Amongst all types of forests, tropical rainforest is the most productive type of forest and rich in term of biodiversity as they provide home to variety of wildlife and tree species (WWF-Malaysia, 2013).

Tropical forests lie in the equatorial region between tropics of cancer (23°N) and tropics of Capricorn (23°S), latitudes that receive constant sunlight throughout the year. According to Nix (2014), the global distribution of tropical rainforests can be divided into four realms which is the Neotropical, Afrotropical, Australian and Indomalayan as shown in Figure 1.1. The Neotropical realm includes the Amazon

River Basin, the largest continuous rainforest on earth. Afrotropical rainforest is mostly located in Congo River Basin and also some in western Africa characterized by dry and seasonal compared to other realm. Most of the Australian rainforest realm is located at New Guinea with only small portion in the northeast part of Australia. The remaining Asia's tropical rainforest is in Indonesia, Malaysia, Cambodia and Laos known as the Indomalayan rainforest in which it is believed to be the oldest rainforest in the world (WWF-Malaysia, 2013). In tropical rainforest, trees can grow up incredibly tall as there is great competition to sunlight. Buttresses can be seen at the base of these huge trees to support their height and stabilize them in shallow forest soil. The structure of tropical rainforests are consists of several vertical layer which is the floor, shrub layer, understory, canopy and the overstorey (Butler, 2013b).

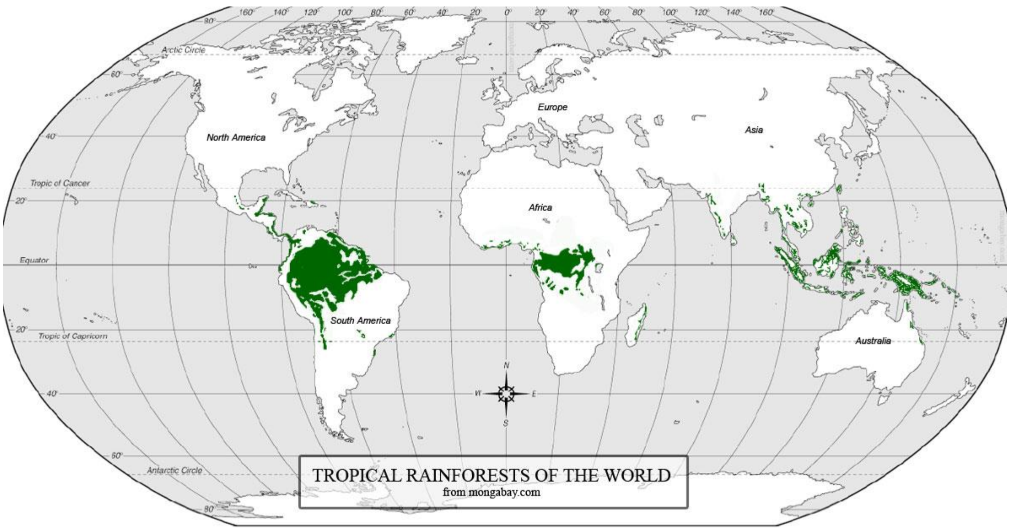

Figure 1.1 Global distribution of Tropical Rainforest (Butler, 2013b)

This study was conducted in Malaysia, one of the country listed as the world's mega-diverse countries as it is ranked twelfth in the world on the National Biodiversity Index (The REDD Desk, 2012). Malaysia has experienced loss of forest area since 1970s where the major factors are decentralised management of forest resources, reforestation, rapid expansion of industrial timber and palm oil industry. According to Butler (2013a), the released of high resolution Google forest map (Figure 1.2) have shown that Malaysia has the highest percentage of forest loss from 2000 to 2012. Planted trees or secondary forests unable to provide the same quality of primary forests in term of biodiversity, carbon sink and maintenance of ecological services in which showing that Malaysia suffered very extensive decrease of natural capital base.

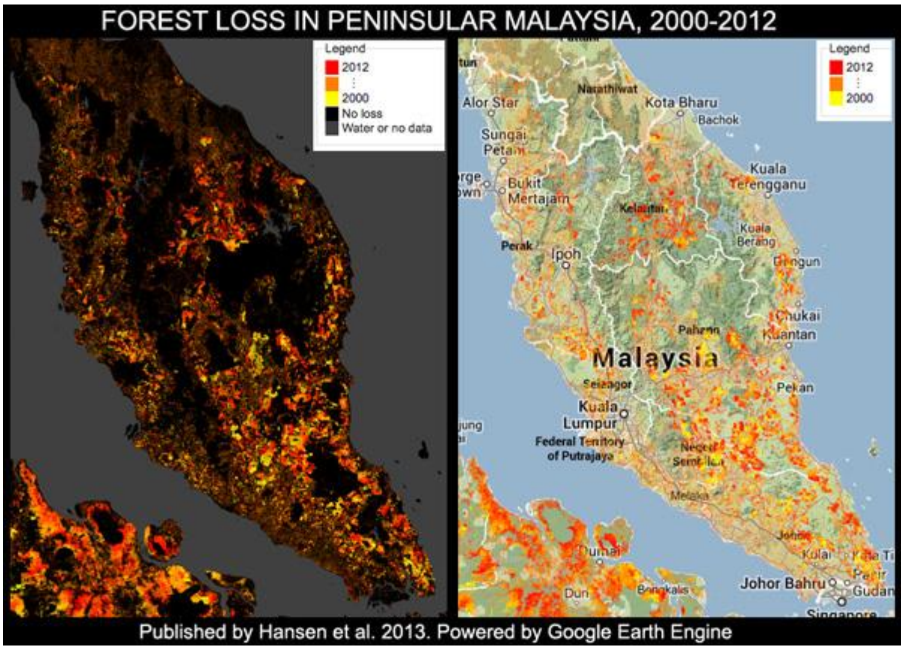

Figure 1.2 Google forest map showing forest loss between 2000 to 2012 (Butler, 2013a)

The United Nation Reduced Emissions from Deforestation and Forest Degradation (REDD) programme has assigned financial value on the biomass and carbon stored in the forests in which has emphasised the importance of forests in carbon sequestration and mitigating climate change. Developing countries are given incentives based on the total land of their forested area (Parker *et al.*, 2008). According to The REDD Desk (2012), Malaysia signed the UNFCCC in June 1992 and agreed to maintain at least 50 per cent of forest area and pledge to reduce 40 per cent of carbon from year 2005 to 2020. Malaysia also signed up to the Kyoto Protocol and take part as observer country to the REDD programme.

Tropical rainforest capable of providing wide range of benefits mainly in ecological services. One of the most significant contributions is to encounter the issue of climate change by sequestering billions of tons of carbon. Forests canopies absorb carbon dioxide (CO_2) from the atmosphere and store the carbon through photosynthesis process in their stem, branches, leaves and roots in which later deposited into soil carbon pool. As stated by FAO (2009), forest monitoring and management activities particularly in quantifying above-ground and below-ground biomass of trees are the essential input in climate change forecasting models. The carbon stock and above-ground biomass terminology will be used interchangeably throughout this study as we acknowledge that biomass is typically 50 per cent of carbon (FAO, 2009). The role of forests in reducing carbon in the atmosphere has been highlighted in United Nations Framework Convention on Climate Change (UNFCCC) and Kyoto Protocol in which member countries are required to provide temporally and spatially fine-gained assessments of carbon stocks (Basuki *et al*., 2009).

Deforestation and forest degradation, specifically in the tropical regions contributes 12-20% of global green gases in the 1900s and early 2000s in which have reduced the future potential of carbon sink from forest area (Saatchi *et al*., 2011). Deforestation activity is one of the major source of carbon as the carbon are released to the atmosphere from the burning and clearing process. Even with only small increase in carbon sink into forest and soil may help in encountering the effect of human-induced carbon dioxide emission. The long term carbon exchange between terrestrial carbon pool and the atmosphere is influenced by changes of forests area and per hectare changes in forest biomass as a result of management and regrowth (Houghton, 2005).

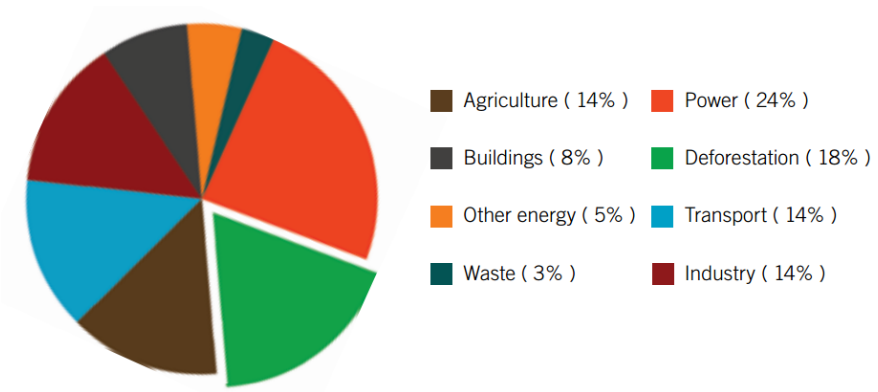

Figure 1.3 Greenhouse gases emission in 2000 by sources (Parker *et al*., 2008)

Billions of dollars will be spent as the compensation by REDD to the developing countries in preservation of their forested area. Considerable efforts have been done in quantifying and mapping the carbon stocks or above-ground biomass and one of the major challenge is the uncertainties and errors in the estimated biomass especially in tropics (Houghton, 2005). The effectiveness of REDD programme in above-ground biomass and carbon stocks mapping is depending on the quality of the data. In the past, people normally estimates carbon or biomass by solely depending on the field measurements, a slow and labour intensive approach that highly anticipated with errors over large area due to sparse sampling. Traditional methods in acquiring forest parameters are time consuming and expensive to conduct. Besides, accurate measurements of biomass from individual trees are currently done through felling and weighing process in which are not practical in operational forestry (Kankare *et al*., 2013a). Conventional method of allometric model development requires trees from various species and sizes to be cut down. Tree components (stem, branches and leaves) from felled trees are separated and weighed separately as individual components of tree biomass (Picard *et al*., 2012). This destructive approach is considered the most accurate methods for field measurement for the time being where it is used to calibrate carbon and biomass estimation using remote sensing technology.

Recent methods for accurate carbon and biomass stock estimation have been driven by remote sensing technology. This remote sensing approach is supported by field measurements data where the biomass estimation is done by calibrating the measurement in the field with the remotely sensed data (Picard *et al.*, 2012; FAO, 2009) .The advancement in remote sensing have introduced laser scanning, a technology capable in describing the three dimensional forest structure from its high density point clouds data. Laser scanning technology is divided into two major platforms which is airborne and terrestrial. Airborne laser scanning capture the point clouds data from airplane providing a wide area coverage while terrestrial laser scanning is done on the ground placed on a tripod in which provides denser point clouds with labour- and cost effective accurate measurement that scales from single tree to plot level. Previous studies have shown that TLS capable in measuring several essential parameters in deriving individual stem volume and biomass estimation such as diameter at breast height, tree height, height to crown base, crown projection area, crown volume (Kankare *et al*., 2013a; Seidel *et al*., 2013; Hopkinson *et al*., 2004; Yao *et al*., 2011; Watt & Donoghue, 2005; Thies *et al*., 2004). Stem biomass contributes 75-85% of total above-ground biomass in Boreal Forest Zone and therefore it must be measured accurately (Kankare *et al.*, 2013a).

There are two approaches in estimating stem biomass of individual trees using TLS which is by (i) using existing allometric models (Seidel *et al.,* 2013; Kankare *et al.,* 2013a; Yao *et al.,* 2011*)*, and (ii) through direct volume to biomass conversion (Feliciano *et al.,* 2014) . Allometric models is the study of relative size of plant parts and relationships between tree parameter such as diameter at breast height, tree height and tree species with total above-ground biomass. The models are highly affected by uncertainties and errors during the development. General models were normally developed to cope with multi-species and multi-site while some models are site-specific in which supposedly able to provide better biomass estimation over the same forest environment (Seidel *et al*., 2013). The direct volume to biomass conversion can be done by multiplying volume of the stem with wood density as different tree species will have different density (Feliciano *et al*., 2014). The second method is more likely to produce a better estimation of stem biomass thus contributes to better estimation of total above-ground biomass.

Many studies have been conducted using terrestrial laser scanning in tree measurements (Yao *et al*., 2011; Watt & Donoghue, 2005; Bucksch *et al*., 2009; Raumonen *et al*., 2013; Thies *et al*., 2004; Hopkinson *et al*., 2004) and pre-harvest biomass estimation (Kankare *et al.*, 2013a; Seidel *et al.*, 2013; Feliciano *et al.*, 2014; Yao *et al.*, 2011) to assess the accuracy and reliability of this technology in practical forestry. However, the use of terrestrial laser scanning in biomass estimation using volume to biomass conversion especially in tropical rainforest are still unclear. Further study and development should be focussing on applying this technology in complex forest structure of tropical rainforest and replacing the destructive conventional methods. The purpose of this study is to introduce a non-destructive laser-based method for above-ground biomass estimation of dominant tree species in Malaysia rainforest.

1.2 Problem Statement

Measurement of biomass and carbon stock has become increasingly important especially one contributed by vegetation (Yao *et al*., 2011). Inevitably, large-scale estimation of carbon stock and biomass is heavily relied on the availability of allometric equation that allows estimation to be made accurately at individual tree level. However, the availability of local allometric equation is hindered by several factors including conventional approach in determining such equation, which usually based on a time consuming and expensive destructive sampling method (Singh *et al.,* 2011; Basuki *et al.,* 2009; Ketterings *et al.,* 2001). This further complicates by the fact that the equation is usually tree species, topographic and local climatic dependent (Chen *et al.,* 2012; Næsset & Gobakken, 2008; Ni-Meister *et al.,* 2010).

Besides, allometric equation only employing several easy to measure tree parameters such as diameter at breast height, tree height and tree species (Chave *et al*., 2014) which contain insufficient information from the crown structure. Crown biomass is assembled from combination of leaves and branch biomass (Kato *et al.,* 1978; Kankare *et al.,* 2013a) where the parameters in describing the crown structure using conventional methods are time consuming and requires tremendous effort. Therefore, not enough attention were given on the crown biomass in which it is generally estimated using allometric equation in relationship with the stem biomass (Kato *et al*., 1978). Kankare *et al*., (2013a) have studied several biomass estimation models and one of the models does not employed information of crown structure and contributes errors for crown biomass during growing seasons in boreal zone. This crown size information might be considered as a source of error in crown biomass estimation in tropical rainforest with high density of crown structure throughout the year. Another method of converting volume of the stem directly to biomass supposed to give better estimation of biomass but still it requires destructive sampling.

Recent methods for detailed and accurate carbon and biomass stock estimation over large area have been driven by remote sensing technology. However, indirect or inference methods from optical remote sensing and radar backscatter are regularly inaccurate due to shadowing effects (Gemmell, 1995) and signal saturation (Hamdan *et al*., 2011). Nowadays, LiDAR-based remote sensing approach has been used effectively for detailed measurement of man-made and natural objects. The geometry of any object can easily reconstructed from point clouds and detailed measurement can be carried out on the object. Airborne and terrestrial LiDAR have been used to estimate above-ground biomass of vegetation at different scales and details (Yao *et al.*, 2011; Hauglin *et al.*, 2014; Lucas *et al.*, 2006; Zhao *et al.*, 2009). The scientific community has been exposed to significant increase in the availability of different global satellite data with various spatial and spectral resolutions. However, the use of these data is currently not supported by accurate field data in which most of allometric equations developed are based on easily measured tree parameter which is DBH (Brown *et al.*, 1989; Basuki *et al.*, 2009; Chave *et al.*, 2014; Kato *et al.*, 1978).

Terrestrial LiDAR have proven to be useful in providing detailed measurement of single tree, which is mostly required for development of allometric equation and estimation of individual tree above-ground biomass (Yao *et al*., 2011). Feliciano *et al*. (2014) have applied terrestrial LiDAR to measure stem volume at different height and quantify biomass of individual trees providing a non-destructive volume to biomass conversion method. Effort of utilizing terrestrial LiDAR for biomass estimation is still very limited and its advantage and limitation over tropical rainforest remain unclear. Challenge arise when using denser point cloud data from terrestrial LiDAR in tropical rainforest because the data is easily affected by noise and occlusion from overlapping emergent trees. Scanning position were configured to cope with the topography. Placement of scanning position also must consider the size of the tree because huge trees requires scanning distance of half the height of the tree according to the scan angle range of the scanner to cover the information of the crown structure. Therefore, all these factors must be thoroughly investigated to determine the effectiveness of terrestrial LiDAR in tropical rainforest. The purpose of this study is to evaluate the effectiveness of non-destructive laser based method for aboveground biomass estimation of dominant tree species in Malaysia rainforest. This is a novel method that combines detailed measurements of single tree with supplementary data of wood and leaf density in which so far has never been tested by previous studies. Development of terrestrial LiDAR technology and study in this field of research is crucial which enables generation of a more effective and reliable ground data that could replace the conventional method.

1.3 Research Objectives

The aim of this research is to estimate the above-ground biomass using non-destructive laser scanning approach for selective tree species in Malaysia’s tropical rainforest. This aim is supported by several specific objectives:

i) To develop a semi-automatic method of individual tree measurement based on detailed geometric reconstruction of different tree parts from point clouds.

ii) To estimate individual tree total above-ground biomass based on TLS derived tree parameters and field collected data (i.e. tree species, wood density and leaf density).

iii) To assess the estimated tree properties and biomass obtained from laser scanning method with field collected data and available allometric equation.

iv) To improvise available allometric aboveground biomass models for aboveground biomass estimation based on tree species and individual tree properties obtained from TLS.

1.4 Research Questions

i) To develop a semi-automatic method of individual tree measurement based on detailed geometric reconstruction of different tree parts from point clouds.

a) How accurate the measurement of stem (eg. diameter at breast height and volume) based on cylinder fitting applied on the point clouds surface?
b) How accurate the tree height measured from point clouds compared to the tree height derived from allometric models?

ii) To estimate individual tree total above-ground biomass based on TLS derived tree parameters and field collected data (i.e. tree species, wood density and leaf density).

a) Is it feasible to estimate branches and leaves biomass solely from TLS data?

b) How much improvement does supplementary information from crown structure provides on TAGB estimation?

iii) To assess the estimated tree properties and biomass obtained from laser scanning method with field collected data and available allometric equation.

a) How close is biomass estimated for every tree component from TLS in comparison with existing allometric model?

b) How significant are the tree parameters (DBH, tree height, crown base height, stem volume, branches and leaves volume measured from TLS data) in biomass estimation?

c) Does the size of the tree influence the accuracy of the measurements?

iv) To improvise available allometric aboveground biomass models for aboveground biomass estimation based on individual tree properties obtained from TLS.

a) What is the relationship between TLS estimated stem, branches and leaves volume with stem, branches and leaves biomass?

b) What is the relationship between tree parameters estimated from TLS with TAGB?

c) How much improvement does species-specific relationships contributes to regression models?

1.5 Significance of Study

According to UN-REDD Programme (2009), Reducing emissions from Deforestation and Forest Degradation (REDD) is an effort to create a financial value for the carbon stored in forests. REDD offer incentives for developing countries to reduce emissions from forested lands and invest in low-carbon paths to sustainable developments. Malaysia have also prepared on the roadmap to REDD+ implementation consists of strategy, scope, financing and management structure (NRE, 2011). Detailed forest inventory and mensuration of individual trees for the purpose of biomass estimation have drawn attention of research society mainly to support sustainable forest management and global carbon sequestration. This study will utilize terrestrial laser scanning, a ground-based remote sensing technique that capable in retrieving three dimensional vegetation structure in high detail for aboveground biomass estimation. Traditional methods in acquiring forest parameters are time consuming and expensive to conduct. Accurate quantification of biomass from individual trees are currently done through felling and weighing process in which are not practical in operational forestry.

This study is an effort to produce a non-destructive method for individual tree or plot-level biomass estimation. Through the reconstruction of the individual tree parts, tree parameters such as diameter at different level of height, tree height, height to crown base and stem volume can be computed digitally with high accuracy using dense terrestrial LiDAR point clouds. The measurement from TLS also include the crown metrics which is hard to measure in forest inventory and basically are modelled based on other easily measured tree parameters such as height and diameter at breast height. Direct measurement from TLS is expected to provide more effective tree measurement and biomass estimation in which will be investigated throughout this study. Multi-scan approach (Hauglin *et al*., 2014; Hopkinson *et al*., 2004; Kankare *et al*., 2013a) employed in this study will provide detailed datasets that can be used in tree components reconstruction to measure stem, branches and leaves volume directly from the point clouds, providing a geometrical approach of biomass estimation rather than depending on allometric equations (Yao *et al*., 2011).

This study will promote terrestrial laser scanning as a viable option for a fast and accurate aboveground biomass estimation compared to conventional methods. Local agencies such as Forest Research Institute of Malaysia (FRIM) which is actively involved with monitoring carbon changes in Peninsular Malaysia and Borneo region can get exposed to this kind of technology and utilize it in forest measurement. This study also capable in proving that TLS also can be used effectively in precision agriculture to effectively monitor growth of individual trees through temporal measurements of tree attributes in which is also currently researched by Malaysia Rubber Board (LGM). This technology will provide a non-destructive pre-harvest measurement and biomass estimation in determining the value of individual trees. Therefore, the output of this study which is the biomass estimation in the plot level using state-of-the-art terrestrial LiDAR technology can be seen as a future potential in replacing the destructive conventional methods for sustainable forest management in Malaysia rainforest.

1.6 Scope of Study

This study is conducted in Royal Belum State Park located at 45 kilometers from Gerik, Perak in Malaysia. Primary data collected for this study is high density point clouds data generated from Riegl VZ400, a time-of-flight terrestrial laser scanner for 35 forest plots that includes various sizes of dominant trees and some parts of understory vegetation. However, trees from only several plots were used for this study due to manually intensive individual tree extraction and time constraint. This study is also based on biomass estimation on individual trees level not on stand-level measurement because this study is focusing on developing a tool for detail biomass estimation of individual trees in which the tool is still under development.

Besides, this kind of study is still uncommon in tropical rainforest where most of the study and practical forestry works done by the local institutions such as Forest Research Institute of Malaysia (FRIM) are depending solely on utilizing the existing allometric models. The point clouds from different scanning position were registered into a relative projected coordinate system and not assigned into local coordinate system because this study only focused on the tree measurements and development of biomass estimation model which does not require precise positioning of points to represents the real world. Every plots have radius of 12.6 meters, scanned with 4 positions, which covers the centre and 3 edge locations of the forest plot with distance approximately 2 meters from the plot boundary. Each scanning position was selected based on the location of trees and the condition of the terrain. This multi-scan approach is the only way to cover any occluded trees from any scanning station and to get as much data as possible considering the gigantic size of trees, huge creepers twine over trees and topography of the surrounding area. Measurement is carried out on individual tree by separating it with neighboring and understory vegetation that may complicate the processing stage.

Previous studies have shown that point cloud generated from terrestrial laser scanning can be used to retrieve several tree parameters such as tree height, height to crown base, diameter at breast height, trunk volume, crown projection area, crown volume, leaf area index. However, this study only focused on measuring the crucial parameters for biomass estimation which is diameter at breast height, tree height, height to crown base, stem volume, branches volume, leaves volume and crown volume. The selection of parameters is based on the previous studies on volume to biomass conversion and the available biometric data. The estimated stem volume is measured roughly using point cloud fitting method without any validation because validation can only be done by cutting down trees and measure every dimension of its stem in which have not been done anymore by any local institution or forestry department. Same goes to the estimated biomass in which the results can only be compared with the existing allometric models to see the reliability of this methods. Further study on this matter is required to assess the accuracy of the trunk volume measured from point clouds data that will contribute errors in the biomass estimation and to see how accurate biomass estimation using this method.

1.7 Description of Study Area

This study is carried out at the northern part of Peninsular Malaysia in Royal Belum State Park, Gerik in the state of Perak. The coordinate of the area is around 5º 33’ 25.68” N and 101º38’29.41” E, located at 230km away from Ipoh and 430.5km from Kuala Lumpur. This area receiving 1998 to 2300mm of mean annual rainfall, varies throughout the year. Royal Belum State Park is considered as one of the World’s oldest rainforest which is believed to have been existence for more than 130 million years, older than the Amazon and the Congo. According to (WWF-Malaysia, 2013), Royal Belum State Park (RBSP) was gazetted as a protected area on 3 May 2007 under the Perak State Parks Corporation Enactment 2001. The park covers a total area of 117,500ha in the most northerly region of the State of Perak in northern Peninsular Malaysia. RBSP lies between border of Thailand on the north, the state of Kelantan to the east and Sungai Gadong in the west. Royal Belum State Park consists of forest, grassland, abandoned agricultural plots, and a large man-made lake, Tasik Temenggor. Forest types found here are mainly lowland dipterocarp, hill dipterocarp and upper dipterocarp. The majority of species are characteristic of tropical rainforest in Peninsular Malaysia, Sumatra and Bornea such as Meranti and Keruing.

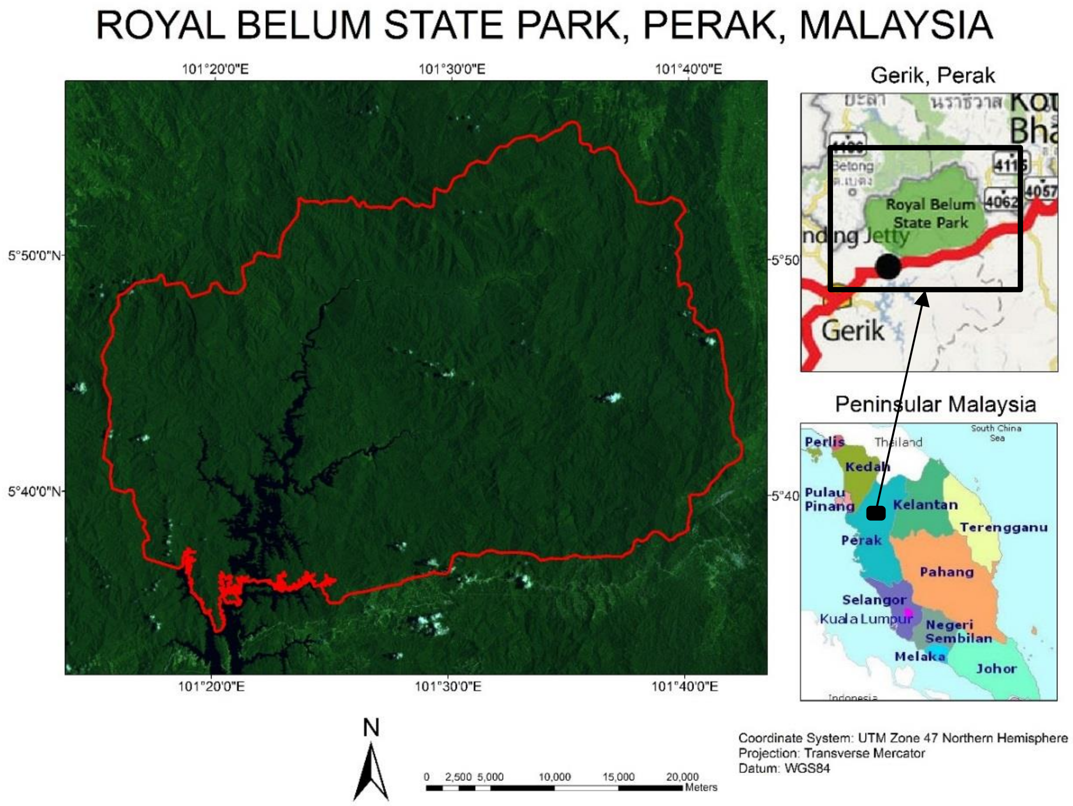

Figure 1.4 Map and Boundary (red boundary) of in Royal Belum Forest Reserve, Gerik, Perak, Malaysia

1.8 Thesis Outline

This thesis consists of five chapters in which each chapter are separated systematically to clearly show the significance of this study towards sustainable biomass estimation using state-of-the-art terrestrial laser scanner (TLS). **Chapter 1** contains sub-chapters that drive the initiative in conducting this research with background of study showing roles of aboveground biomass in carbon cycle modelling and the importance of accurate aboveground biomass estimation according to REDD Programme under United Nation. This chapter also stated the problem faced with conventional approach and previous study using TLS in tree measurements and aboveground biomass estimation. Objectives and research questions developed were also outlined in this thesis as a guideline throughout the study. Significance of study discussed on the contributions of this study to knowledge on the usage of TLS in forestry applications particularly in aboveground biomass estimation. Furthermore, this sub-chapter discussed on potential local agencies that has shown interest in the use of TLS in forestry or agricultural in terms of accurate tree measurements and tree growth monitoring. Scope and limitation of this study also presented in this chapter to ensure that this study can be completed within proposed timeframe.

Chapter 2 summarizes reviews from relevant literatures in which this chapter discusses on the advancement of remote sensing technology particularly in forest biomass mapping and tree measurements from conventional method to satellite-based and to laser-based approach. This chapter also highlighted problems faced from the development of allometric equations from conventional method and also insufficient studies on using TLS for biomass estimation in tropical rainforest that will be partially fulfilled by this study. **Chapter 3** are fully devoted to introduce datasets and several methodologies used in this study. Methodologies highlighted are plot configuration in the field, semi-automatic measurements of tree attributes from TLS point cloud data and volume-to-biomass conversion that derived the TLS-estimated individual tree aboveground biomass. Methods of validation were also discussed in which tree semi-automatic tree measurements are validated using biometric data while aboveground biomass were validated using existing allometric equation (Kato *et al*., 1978) suited for the purpose of this study.

Chapter 4 focusses on presenting and discussing the results from data processing outlined in **Chapter 3**. This chapter shows detailed results from data preparation in pre-processing phase in which includes point cloud registration, multi-station adjustment, individual tree extraction, and separation of point clouds from different tree components. Distribution of tree sizes and tree species and number of trees involved in this study are shown in descriptive statistics. Besides, this chapter also discussed on the accuracy of tree measurements obtained from TLS in which most of the discussion is about the problems of tree height measured from TLS that causes from multi-layered trees that obstruct the laser pulses from reaching the tree tops. Crown base height (CBH) measurement are subjective to error due to absent of any markings on the tree at CBH position during data collection in the field. Diameter at breast height shows as the best tree attributes that can be derived from TLS. Volume estimation for each of tree components (stem, branches and leaves) were used in conversion into biomass through multiplication with wood and leaves density. Individual tree measurements and aboveground biomass estimation for every tree component were validated with biometric data and existing allometric model. Results obtained were used to develop general and species-specific allometric equations based on existing primary allometric equation.

The results obtained shown in **Chapter 4** are then used in **Chapter 5** to answer all research questions thus proved that objectives from this study were successfully achieved. **Chapter 5** also presented recommendation to improve current status of this study as continuation of this study is highly recommended due to the findings shows by this study which is biomass estimation and development of allometric equations in condition of tropical rainforest using TLS. The overall organization of this thesis is shown in Figure 1.5.

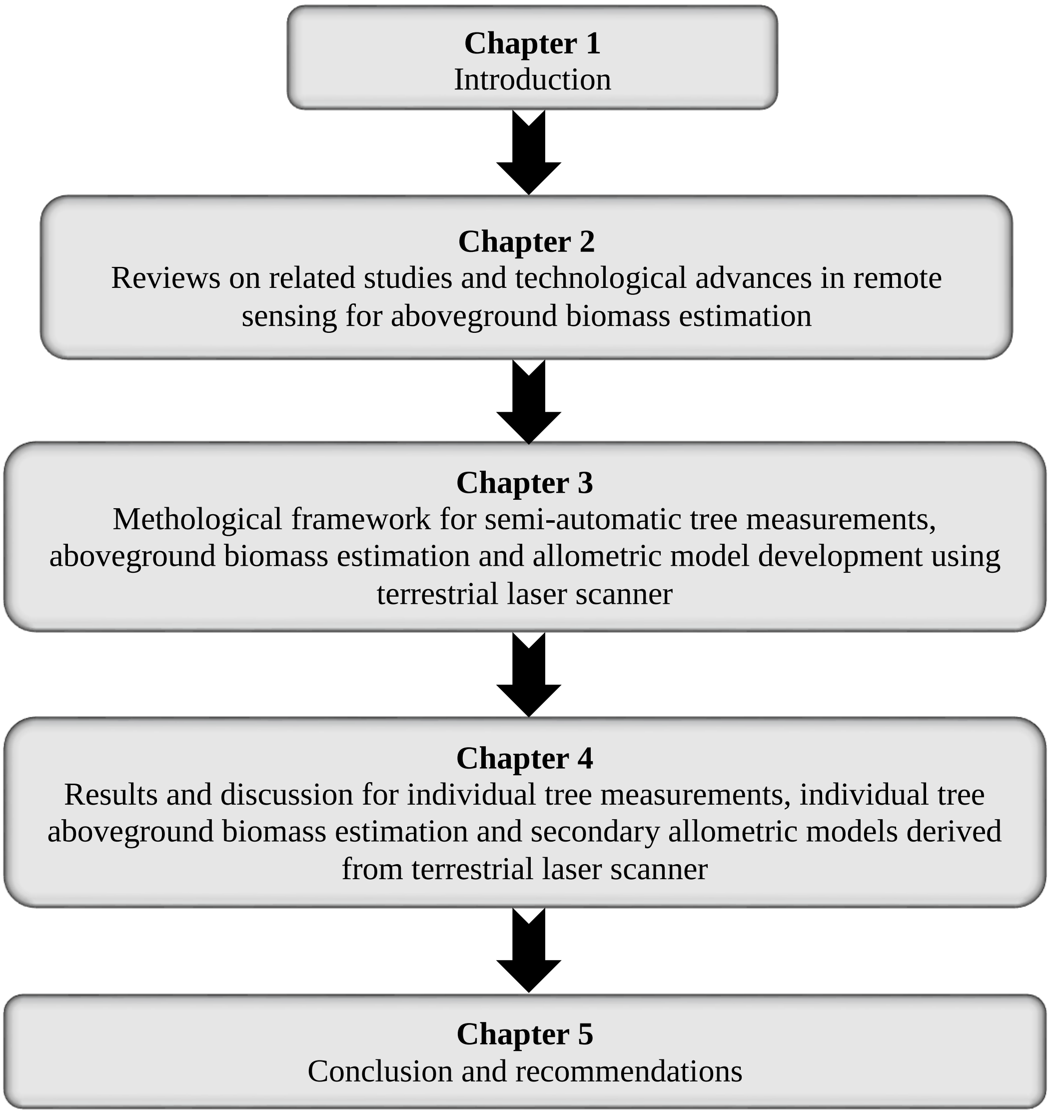

Figure 1.5 Schematic outline of the thesis

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