ACCURACY OF MEASURING TREE HEIGHT USING AIRBORNE LIDAR AND TERRESTRIAL LASER SCANNER AND ITS EFFECT ON ESTIMATING FOREST BIOMASS AND CARBON STOCK IN AYER HITAM TROPICAL RAIN FOREST RESERVE, MALAYSIA

OJOATRE SADADI
February, 2016

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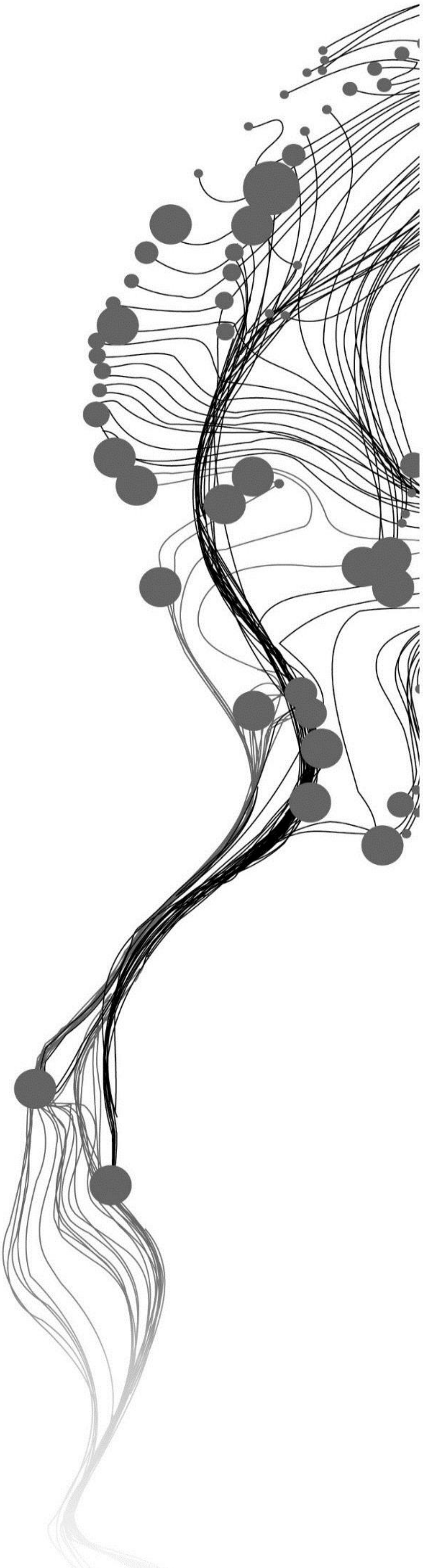

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Enschede, The Netherlands, February 2016.

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
Specialization: Natural Resources Management

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ABSTRACT

Forests play a major role in climate change through their unique nature of carbon sequestration which regulates the global temperatures. They possess high biological diversity, structure, complexity and carbon rich ecosystem. Climate change is directly attributed to changes in global atmospheric conditions over a given period. This requires actions towards its mitigation and hence various bodies have come up with a number of initiatives geared towards combating climate change, for example the UNFCCC with its REDD+ (Reducing Emissions from Deforestation and forest Degradation) program. REDD+ aims at accurately quantifying the sources and sinks of carbon, and therefore has designed Measurement Reporting and Verifications (MRVs) for its implementing countries.

The REDD+ MRVs require accurate measurements. This helps in quantifying the carbon sinks and establish the amount of carbon sequestered. This can be done through various methods for example direct field measurement or using remote sensing techniques. In order to accurately map the tropical rain forest biomass that contains the most significant amount of carbon, IPCC has designed biomass estimation equations. The biomass estimation equations require tree parameters like Height and Diameter at Breast Height (DBH) as an input. Therefore, there is need to measure tree height and diameter at breast height accurately. Studies have shown that, the tree height is one of the most difficult forest parameters to be measured, yet can be mapped and measured accurately using remote sensing most notably LiDAR technology. However, such measurements from remote sensing require validation using field measurement instruments commonly known as hypsometers. Research has shown that these hypsometers have significant error compared to the LiDAR measured tree height. There is no standard set for the height measurement using the hypsometers, and yet the data collected using the hypsometers are considered as the data for validation of the remotely sensed data. This potentially leads to errors which would be minimised. The error is then transferred in to the biomass and carbon estimation. This study therefore aimed at establishing methods that ensure reasonable accuracy of tree height measurement using both Airborne LiDAR and Terrestrial Laser Scanner, with field measurements using hypsometers mainly Leica DISTO 510. Then assess the effects of tree height accuracy on the forest biomass and carbon stock through sensitivity analysis of the error in height measurement and how it effect the accuracy of tree biomass and carbon stock.

Field height measurement using Leica DISTO 510 showed underestimation of tree height with RMSE of 4.20 m while TLS showed underestimation of height with RMSE 1.33 m when Airborne LiDAR was used as a standard to validate the field and TLS measurements. There was significant difference in the amount of AGB and Carbon stock from the three different measurements notably 146.33 Mg of AGB and 68.77 Mg of carbon from field measurements, 170.86 Mg of AGB and 80.31 Mg of carbon from TLS and 179.85 Mg of AGB and 84.53 Mg of carbon from the Airborne LiDAR. Considering the Airborne LiDAR measurement as the most accurate, the AGB and carbon stock from field represent 85.55% of respective total AGB and carbon stick estimation from Airborne LiDAR, Meanwhile TLS measurements reflect 95.02% of respective AGB and carbon stock estimated using Airborne LiDAR as a standard measurement. The results have shown that the amount of AGB and carbon stocks are sensitive to height measurement errors resulting from the various methods used to undertake the measurements, the forest conditions. Airborne LiDAR measures tree height more accurately compared to field measurements using Leica DISTO 510 and TLS as they are terrestrially based and cannot accurately capture the top of trees as Airborne LiDAR.

Keywords: Tropical forest, Biomass, Tree height, Airborne LiDAR, Terrestrial Laser Scanner, Height accuracy, Carbon stock, REDD+ MRV, Errors, Sensitivity analysis, Climate change.

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Ojoatre Sadadi,
Enschede, the Netherlands
February, 2016.

"Dedicated to my Late Father Abdu Mulo Tabu, my source of encouragement and motivation"

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LIST OF ACRONYMS

AGB	Above Ground Biomass
ALS	Airborne LiDAR System
CF	Fraction of Carbon
CHM	Canopy Height Model
DBH	Diameter at Breast Height
DEM	Digital Elevation Model
DGPS	Differential Global Positioning System
DSM	Digital Surface Model
DTM	Digital Terrain Model
ESP	Estimation of Scale Parameter
IGI	Ingenieur-Gesellschaft für Interfaces (Engineering Society of Interfaces)
IMU	Inertia Measurement Unit
IPCC	Intergovernmental Panel on Climate Change
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
LiDAR	Light Detection And Ranging
MRV	Monitoring Reporting and Verification
MSA	Multi Station Adjustment
OBIA	Object Based Image Analysis
QSM	Quantitative Structure Models
REDD	Reducing Emission from Deforestation and Forest Degradation
RMSE	Root Mean Square Error
SOCS	Scanner Own Coordinate System
TIN	Triangulated Irregular Networks
TLS	Terrestrial Laser Scanning
UNFCCC	United Nations Framework Convention on Climate Change
UPM	University Putra Malaysia

1. INTRODUCTION

1.1. Background

Forests play a major role in global warming and climate change through their unique nature of carbon sinks and sources (Karna et al., 2013). To estimate the magnitude of these sources and sinks needs a reliable assessment of the amount of biomass of the forests that are undergoing change (Brown, 1997). Forest biomass indicates the amount of carbon sequestered or released by terrestrial ecosystems and the atmosphere of which carbon constitutes 50% of the dry biomass and 25% fresh biomass. Therefore, measuring the amount of forest biomass enables the understanding of the global carbon cycle (Zhang et al., 2014). The tropical rainforests hold high biological diversity, structure, complexity and carbon rich ecosystem (Asmoro, 2014). Different forestry activities have mixed effects on a forest's capacity for carbon sequestration (Wang et al., 2013). The United Nations Framework Convention on Climate Change (UNFCCC) requires emission and removal of carbon dioxide to be reduced from land use, land use change and forest conversion activities which comprise; deforestation, degradation, afforestation and reforestation (Patenaude et al., 2004). These directly have influence on the capacity of the forests to reduce global warming and consequently climate change.

Climate change is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and it is in addition to natural climate variability observed over comparable time frame (UNFCCC, 1992). This is mainly through activities like deforestation, reliance on fossil fuels as well as land use change that emit carbon dioxide in to the atmosphere (Karsenty et al., 2003). In order to constraint climate change, the Reduce Emissions from Deforestation and forest Degradation program (REDD) has been initiated, with its measurement, reporting and verification (MRV) system. The MRV seeks to obtain highly accurate data of forest carbon stocks to ensure transparency. When the MRVs are adopted by the REDD+ implementing countries, it will be used to determine compensation for countries sequestrating carbon and charge those emitting carbon (REDD, 2012).

Accurate measurement of forest biomass and its changes is one of the greatest challenges in the programs that aim at reducing global emissions of carbon from deforestation and degradation of forests (Kankare et al., 2013). The most accurate measurement of biomass would involve destructive methods by cutting the tree and weighing all parts (Brown, 2002). Nonetheless, above the ground forest biomass can be estimated non-destructively through measurement of forest tree parameters like stem diameter, tree height or wood density (UN-REDD, 2013). In order to carry out accurate measurement of the tree height, remote sensing tools have been used. A number of studies on biomass estimation using remote sensing techniques have been undertaken. For example, studies to automatically determine forest inventory parameters from LiDAR point cloud data (Mengesha et al., 2014).

The tree height and DBH (Diameter at Breast Height) are the most important parameters for estimating the biomass (Asmoro, 2014). LiDAR (Light Detection and Ranging), which uses laser technology, is a relatively recent active remote sensing technology which can provide appraisal of tree height (Kumar, 2012). Besides airborne LiDAR, terrestrial laser scanning (TLS) has been used for forest biomass assessment in the recent years. The application of TLS provides a fast, efficient and automatic means for the determination of basic inventory parameters such as the number and position of trees, DBH, tree height and crown shape parameters (Bienert et al., 2006). The measurements from the Airborne LiDAR and TLS need ground truthing, however, the instruments used to carry out ground truth collection are associated with measurement errors.

Tree heights for ground truth are usually measured indirectly using hypsometers. The hypsometers use trigonometric or geometric principles (Bonham, 2013). The widely used hypsometers are based on trigonometric principles for tree height measurement (Van, 2009). These include; Abney level, Haga altimeter, Blume-Leiss altimeters and Suunto clinometer. Their measurement accuracy is approximately ± 1-2 meters (Dale, 1968). However, Bonham (2013) indicates that, tree height may not be accurately measured with the hypsometers due to heterogeneity in the terrain and variation in heights of different trees. Recently, digital hypsometer have been introduced with improved accuracy (Husch et al, 2003). These include the laser distance and range finders with accuracy approximately ± 0.50 – 0.75 meters (Bragg, 2008; Clark et al., 2000; Lois, 1998), laser was also confirmed to be accurate when compared with clinometer instrument (Williams et al., 1994). Despite the errors associated, the height measurements from the hypsometers are used as ground truth for validating remotely sensed data.

Nonetheless, Ene et al., (2012) reveals that several studies have shown that the airborne LiDAR offer very high accurate tree height data. The tree height measurement accuracy from LiDAR ranges between ± 0.05 - 0.10 meters (Andersen et al, 2014). The laser system accurately estimate full spatial variability of forest carbon stock with low to medium uncertainties (Gibbs et al., 2007). The uncertainties exist because the above ground forest biomass is related to several vegetation structural parameters like DBH, tree height, wood density and branch distribution. However, height is the only structural parameter which is directly measured by the Airborne LiDAR (Ni-Meister et al., 2010). Moreover, this has to be validated with field data obtained using height measurement instruments (hypsometers) which have some level of errors. Therefore, it is vital to assess and compare the accuracy of tree height measurement using Airborne LiDAR and Terrestrial Laser Scanner for estimating the above ground biomass (AGB) and carbon. This offers the potential to establish a method that can be used to obtain accurate tree height data for estimating above the ground tropical rainforest biomass. This can significantly contribute to the REDD+ measurement reporting and verification (MRV) system.

1.2. Research Problem

REDD+ has evolved and transformed as a climate change mitigation framework (REDD, 2012). With its many objectives aimed at conserving nature. The main focus is on forest carbon sequestration in order to mitigate emissions. However, the amount of carbon in the forest has to be quantified (Angelsen et al., 2012), hence MRVs that ensure accurate measurements in order to quantify and value the ecosystem services or conservation value notably the forest biomass.

The MRVs seek accurate data mainly to quantify the forest biomass. This is through the AGB and consequently carbon stock. Estimating AGB requires models that are based on forest parameters. These forest parameters include; tree height, DBH, crown diameter among others. The forest parameters can be measured directly or indirectly. However, direct measurement consumes a lot of time and cost. In order to efficiently and quickly quantify the AGB, remote sensing tools have been used. These tools observe directly the tree height which contributes about 50% input to the biomass estimation models (Chave et al., 2014). Chave et al., (2005) confirmed that tree height measurement in tropical rain forest is very problematic. However, the remotely sensed data has to be validated using the ground truth measured from the field using instruments like hypsometers. The bottleneck is that the hypsometers possess measurement errors, with no standard acceptable accuracy to their measurement (Vic et al., 1995). This potentially affects the accuracy of height and consequently the AGB and carbon stock estimation of the tropical rain forests.

Ensuring reasonable accuracy in the height measurement is critical since tree height contributes 50% towards estimating AGB and carbon stock. The forest biomass is estimated based on forest inventory which requires, statistical inventory of growing trees, models to evaluate biomass from the dimensions of the individual trees measured and an evaluation of the biomass contained in standing dead wood and under storey vegetation (Breu et al., 2012). Based on the inventory, two methods are used to estimate tree carbon (Dietz & Kuyah, 2011): 1) using biomass content table, 2) use of models to estimate tree volume, wood density and nutrient content. These approaches are used to construct the allometric equations where height measurement is very essential as an input. Inaccurate tree height measurement leads to inaccurate estimation of the AGB and consequently carbon stock (Molto et al., 2013). Despite the fact that various studies have been undertaken on forest biomass estimation using Airborne LiDAR and TLS, a limited number of studies to the knowledge, have compared the accuracy of tree height measurement using the approaches (ALS and TLS) as well field measurement in a low land tropical rain forest of Ayer Hitam, Malaysia and thereby assess their height measurement accuracy on the amount of AGB/Carbon stock.

Therefore, the aim of this study was to establish methods that can ensure reasonable accuracy of the tree height measurement using the field measurment, TLS and the Airborne LiDAR. Compare the accuracy of tree height measurements from field and TLS with Airborne LiDAR and assess the effects of the error on the estimation of tropical rain forest above ground biomass and carbon stock in Ayer Hitam tropical lowland rain forest reserve in Malaysia.

1.3. Research Objectives

1.3.1. General Objective

To establish methods of ensuring accuracy of measuring tree height using Airborne LiDAR, TLS and field measurement and assess the effects of error on the estimation of forest biomass and carbon stock in Ayer Hitam tropical rain forest reserve in Malaysia.

1.3.2. Specific Objectives

1. To assess the accuracy and compare tree height from field, TLS with Airborne LiDAR data.
2. To estimate and compare the amount of biomass from selected trees using the height measurements from field, TLS and Airborne LiDAR and assess and compare their accuracies.
3. To assess the sensitivity/effect of error propagation from height measurement on the AGB and carbon stock using field, TLS and Airborne LiDAR.

1.4. Research Questions

1. What is the difference between the accuracy of the tree height from field, TLS and Airborne LiDAR?
2. What is the amount of biomass from selected trees using the height measurements from field, TLS and Airborne LiDAR with their different accuracies?
3. What are the effects of errors of height measurements on biomass/carbon estimation using field, TLS and Airborne LiDAR measured height?

1.5. Hypotheses

1. H_0: There is no difference between the accuracy of the tree height from field, TLS and Airborne LiDAR.
   H_1: There is a difference between the accuracy of the tree height from field, TLS and Airborne LiDAR.

2. H_0: There is no difference between the amount of biomass from selected trees using the height measurements from field, TLS and Airborne LiDAR with different accuracies.

H_1: There is a difference between the amount of biomass from selected trees using the height measurements from field, TLS and Airborne LiDAR with different accuracies.

3. H_0: There are no effects of height measurement errors on biomass and carbon estimation.
   H_1: There are effects of height measurement errors on biomass and carbon estimation.

1.6. Conceptual Diagram

The conceptual diagram was developed after definition of the problem for this study, the relevant systems that interact together and the data needs were identified, and this was coupled with the identification of the organisations and bodies involved in climate change as a global concern. The relationship between the systems and subsystems were defined and how the study fits in to the general problem of Climate change. A number of systems that are relevant to the study were identified. Figure 1-1 shows the conceptual diagram of the main systems and the subsystems.

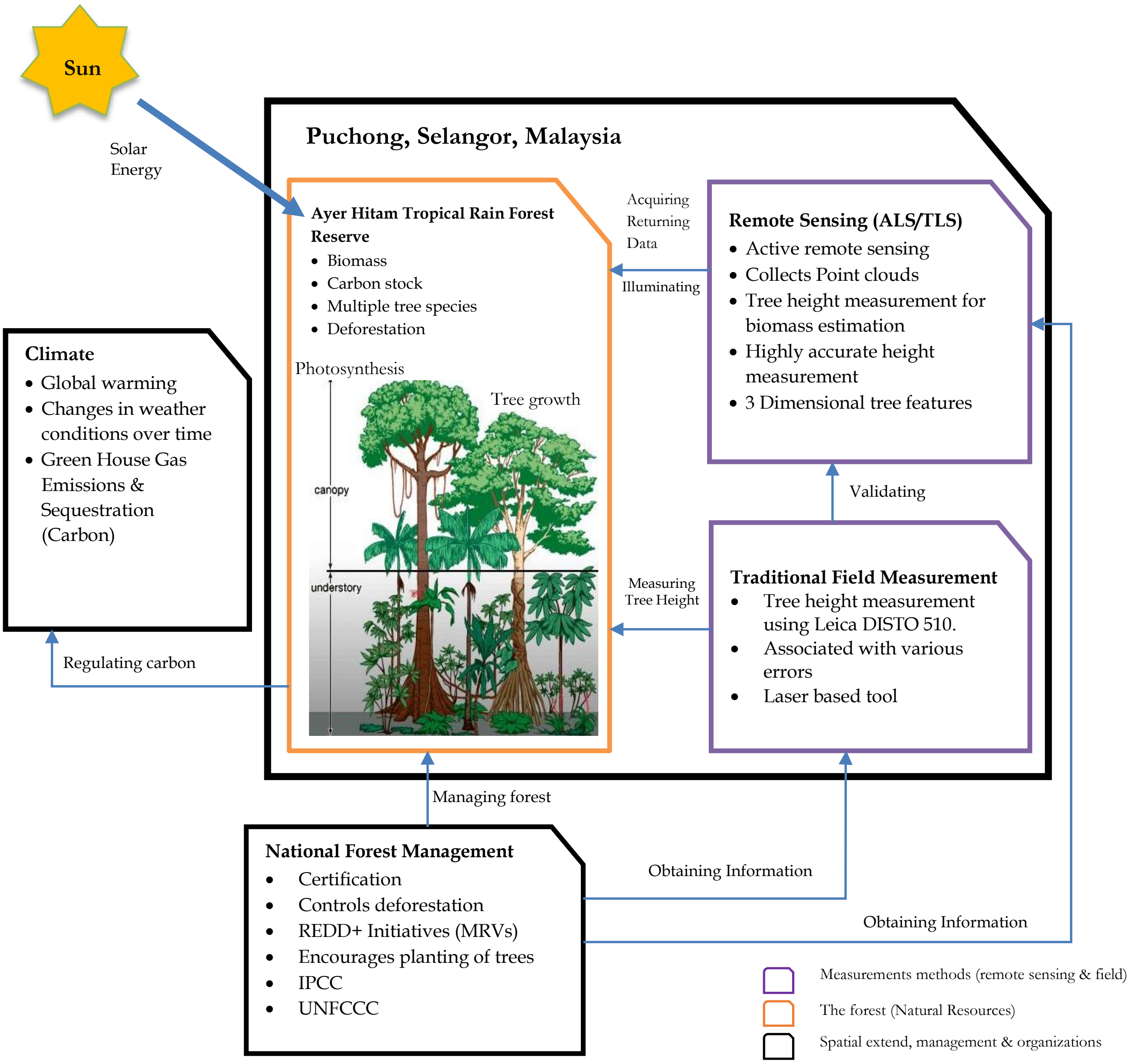


Figure 1-1: Conceptual diagram for the study in Ayer Hitam tropical lowland rainforest

2. LITERATURE REVIEW

2.1. Airborne LiDAR

Airborne LiDAR is an active remote sensing technology which refers to a Light Detection and Ranging. It uses near infrared laser light (1064 nm) and blue green laser light centred at around 532 nm on the electromagnetic spectrum (Schuckman, 2014b). It is commonly referred to as airborne laser scanning system (ALS), this differentiates the LiDAR data acquired from aircraft from the systems that use space borne or terrestrial platforms (Matti et al., 2014). Most latest airborne systems use travel time of a laser pulse to detect the range. They possess three (3) basic components namely (1) a laser scanner, (2) a Global Positioning System (GPS) and (3) an Inertia Measurement Unit (IMU) (Yang et al., 2012).

The laser unit determines the range between the aircraft and the object based on the pulse travel time of the emitted and reflected pulse. Reflected pulse comes with various intensities (Figure 2-1) based on the surface features (Yang et al., 2012).

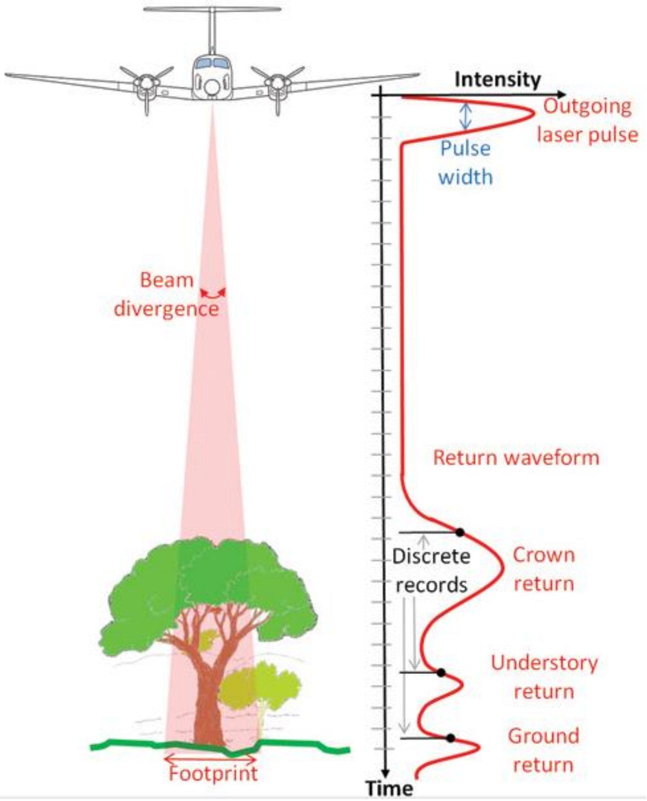


Figure 2-1: LiDAR waveform and discrete recording characteristics.
Source: (Fernandez, 2011)

The ALS has the ability to measure the vertical and horizontal structure of the vegetation, this can be used to extract the tree height accurately (Holmgren et al., 2003). The tree height estimation from ALS system could be affected by the footprint diameter hence the accuracy of tree height (Yu et al., 2004).

LiDAR system collects data in either discrete (Figure 2-2) or full waveform (Figure 2-3). Discrete return LiDAR are characterised with small footprint usually with diameter of 20–80 cm (Evans et al., 2009; Wulder & Seemann, 2003). The discrete form usually records one to numerous returns mainly 1 - 4 returns per pulse (Korpela et al., 2009), through the forest cover, in a non-systematic vertical manner. Waveform sensors are usually large-footprint LiDAR, they digitize and record the energy that return to the sensor that is in a fixed distance, this offers a continuous distribution of laser energy for the laser pulse (Schuckman, 2014a).

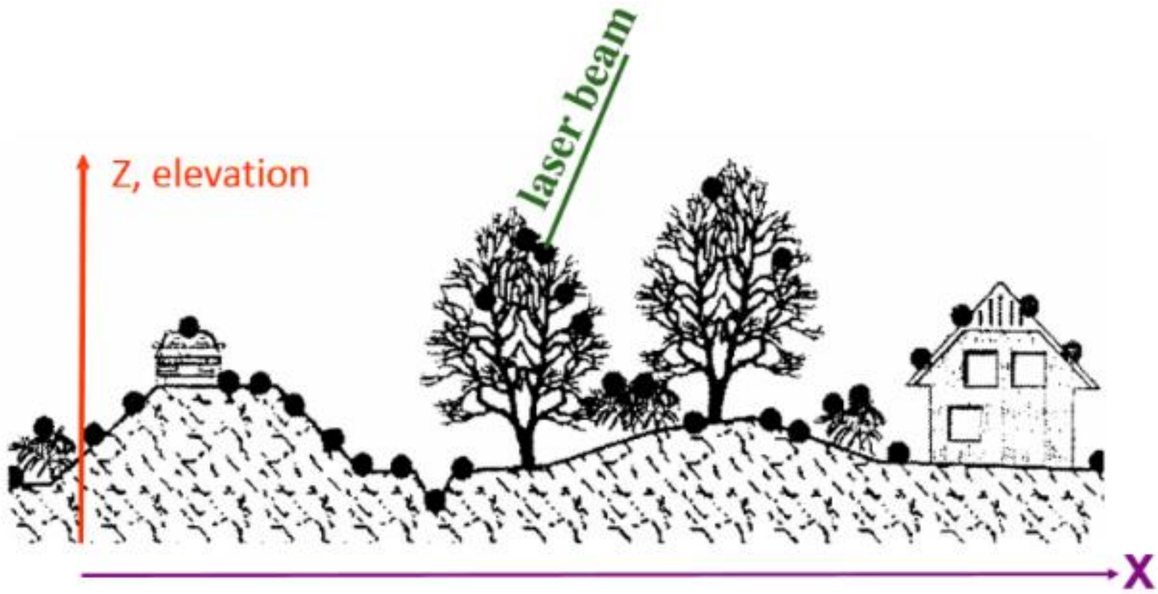


Figure 2-2: Airborne Lidar discrete form data collection system
Source: (Schuckman, 2014a)

Rodarmel et al., (2006) explained that LiDAR whether discrete or full wave form possess a standard accuracy that has to be assessed and validated through direct measurements from the field. A number of studies indicate that the LiDAR system however offer better accuracy than the traditional field measurements using hypsometers.

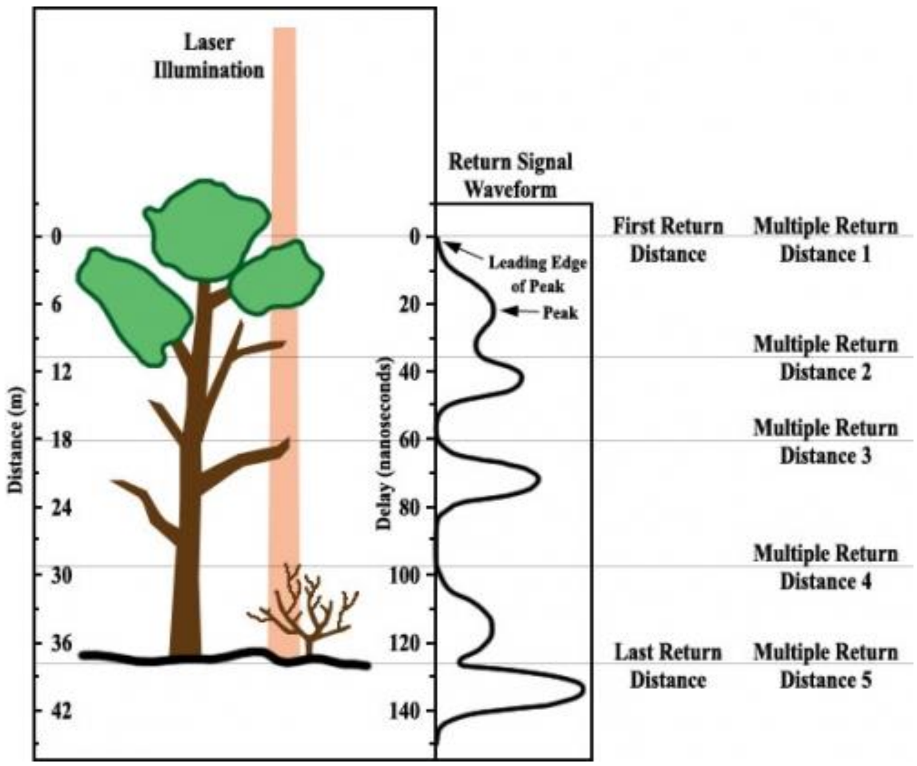


Figure 2-3: Airborne Lidar full waveform data collection system
Source: (Schuckman, 2014a)

The airborne system that was used to collect the data for this study had 0.35 – 0.50 m spot diameter flying between 700 m – 1000 m (Table 2-1).

Table 2-1: Technical specification of Airborne system (LiteMapper 5600 System)

Technical specification (LiteMapper 5600 System)	
Pulse rate	Pulse ranging (full wave form)
Scan angle	60°
Scan pattern	Regular
Beam divergence (mrad)	0.5 mrad
Line/sec	Max 160
Target reflectivity	Min 20% max 60% (Vegetation 30%, cliff 60%)
Flying height	700 m – 1000 m
Laser points/m²	5 - 6 points with swath width 808 m to 1155 m
Spot diameter (laser)	0.35 to 0.50 m
Max (above ground level)	1040 m (3411 ft)

Source: (IGI mbH, 2015)

The LiteMapper 5600 System that provides full surface information with detailed insights in to vertical structure of surface objects, slope, roughness and reflectivity (Hug et al., 2004).

2.2. Terrestrial Laser Scanner

Terrestrial laser scanning (TLS) is a ground-based, active imaging method that rapidly acquires accurate, dense 3 Dimensional (3D) point clouds of irregular object surfaces by laser range finding (Pfeifer et al., 2007). It is becoming a standard for 3D modelling of complex scenes (Barnea et al., 2012). TLS is a technique for high density acquisition of the physical surface of scanned objects, leading to the creation of accurate digital models (Pesci et al., 2011). Figure 2-4 indicates the TLS equipment that was used in this study.

Figure 2-4: RIEGL VZ-400 without camera and with camera.
Source: (RIEGL LMS, 2015).

The number and variety of remote sensing applications of TLS instruments continues to increase (Lichti, 2014). TLS fills the gap between tree scale manual description and wide scale airborne LiDAR measurements (Dassot et al., 2011).

Figure 2-5: Registered scan data from 4 scan positions
Source: (Aalto University, 2013)

Watt & Donoghue (2005) indicated that, the TLS provides a very accurate object range relative to the position of the scanner based on the time taken. The parameters that are easily acquired on forest scene are the DBH, height and the tree density, however the height may be affected by obscurity. The multiple scans can be registered (Figure 2-5) and tree data can be extracted hence height obscurity is minimised. Murgoitio et al., (2014) also reported that, tree parameter of 10 m from TLS using single scan can be visible.

Calders et al., (2015) reported a measured tree height accuracy of R^2 0.98 with root mean square error (RMSE) of 0.55 meters when TLS was used and validated using measurement from destructive sampling. This was carried out using the RIEGL VZ-400 TLS. This further shows the potential of the TLS to provide a highly accurate tree height measurement. Similar studies based on 2 total stations also provided accurate tree parameter estimation (Raumonen et al., 2015). The main objective is to avoid destructive sampling and minimise cost and time using the technology for accurate measurement.

The 3D terrestrial laser scanner RIEGL VZ-400 (Figure 2-4) provides high speed, non-contact data acquisition using a narrow infrared laser beam with an instantaneous scanning mechanism. Very high laser ranging accuracy is based on the unique RIEGL's echo digitization and online waveform processing that permits realisation of better measurement capability even under adverse atmospheric conditions and the appraisal of numerous target echoes. The scanning based on line approach is based on a fast rotating multi-facet polygonal mirror, this offers completely linear, unidirectional and parallel scan lines. The RIEGL VZ-400 is a very compact, lightweight surveying instrument, that can be mounted in any place or under limited space conditions (RIEGL LMS, 2015). Technical specification of RIEGL VZ-400 are listed in Table 2-2.

Table 2-2: Technical specification of RIEGL VZ-400 TLS system

Technical specification (RIEGL VZ-400)	
Ranging method	Pulse ranging (full wave form)
Maximum range (m)	280 - 600
Precision (mm)	3
Accuracy (mm)	5
Beam divergence (mrad)	0.35
Footprint size at 100 m (mm)	30
Measurement rate (kHz)	42 - 122
Line scan angle range (degree)	100
Weight (kg)	9.6

Source: (RIEGL LMS, 2015).

2.3. Tree height measurement

Tree height is an important tree parameter for biomass estimation. Tree height measurement is a critical element of forest inventory. The tree height is the distance along the axis of tree stem between the ground and tree tip (Husch et al., 2003). Obtaining an accurate tree height is one of the greatest challenges in estimating biomass in a tropical rain forest. The accuracy of AGB estimation for individual trees depends on the accuracy of tree height measurement (Hunter et al., 2013). Meanwhile, Bienert et al., (2006) defines tree height obtained from a TLS as "the height difference between the highest point on the point cloud of a tree and the terrain model, accepting that the highest point on the point cloud may not always represent the top of the tree and that a better definition of the representative terrain model point has to be used in rugged terrain".

Tree height can be characterized (Figure 2-6) in to bole height, crown length, commercial bole height, stump height, crown height and merchantable height (Forestry Nepal, 2014; Schuckman, 2014b; Husch et al., 2003)

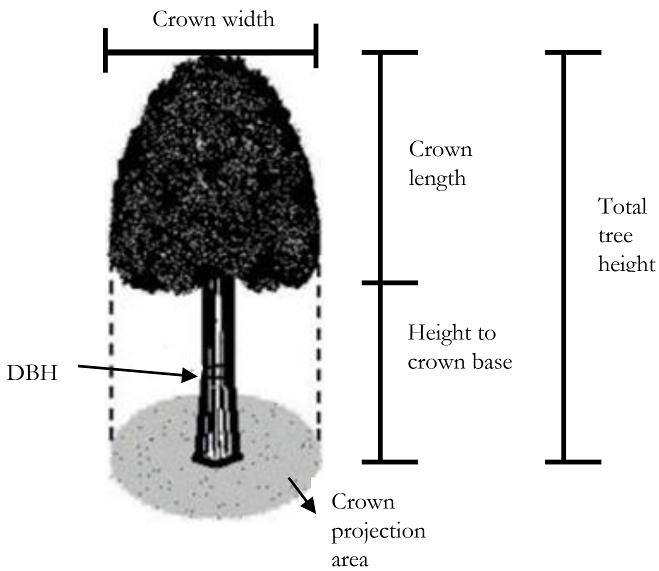


Figure 2-6: Characterization of tree height measurement.
Source: (Schuckman, 2014b)

Bob, (2015) further defines tree height as "the vertical distance between two horizontal planes: one plane passing through the highest twig and the other through the base of the tree at mid-slope". Figure 2-7; shows the tree height profile.

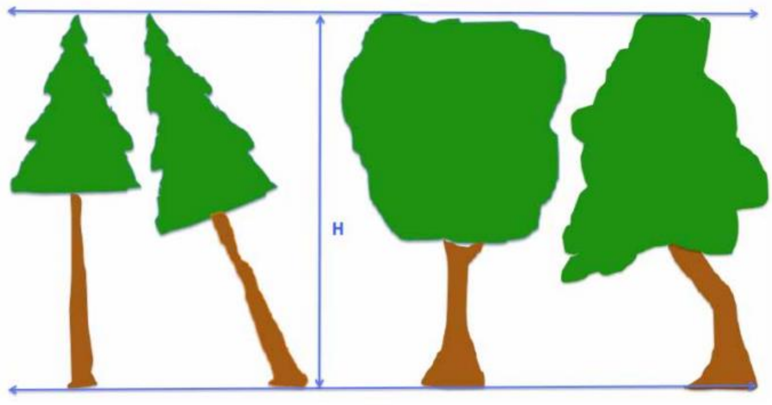


Figure 2-7: Tree height profile
Source: (Bob, 2015)

Various tree species are distributed in different forest types with different height structures. These include, tropical rain forests that hold various tree species with different height characteristics compared to temperate forests (Schmitt et al., 2009). Irrespective of the forest type and species, ALS and TLS can be used to measure the tree height accurately. Accurate height measurements are dependent on forest conditions, observer experience, and the equipment used (Hunter et al., 2013). Tropical rain forests are characterised with significant obstacles for traditional field-based estimate of tree heights, with the dense understory vegetation, tall and wide canopies, and closed canopy conditions that limit the line of sight (Figure 2-8).

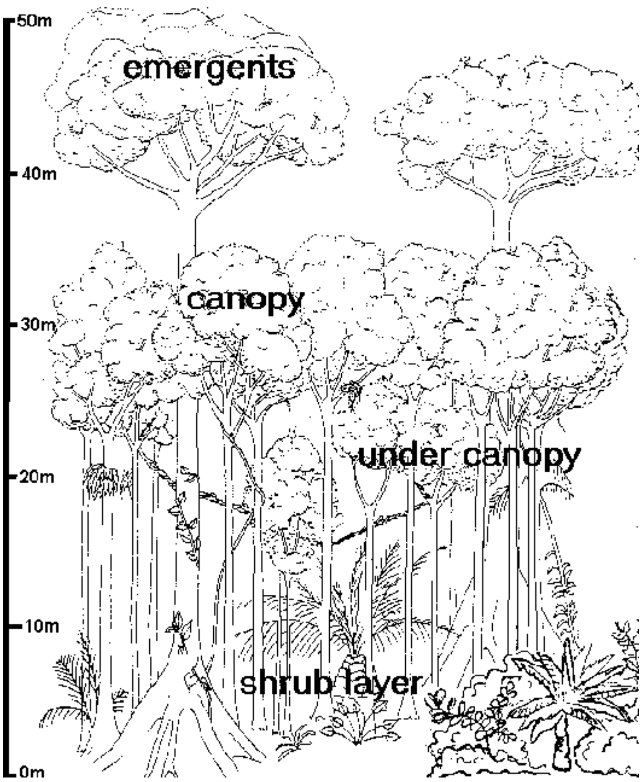


Figure 2-8: Tropical rainforest structure

Source: (Bennett, 2009)

Tree height measurements in tropical rain forests are both labour intensive and have potentially large errors. They are composed of the emergent (the tallest tree), canopy, under canopy and shrub layer (Bennett, 2009) as indicated in Figure 2-8.

The accuracy of tree height measured from ALS can exceed field based measurements. The ALS provides accurate height measurements both from single tree and plot level compared to field measurements (Leeuwen et al, 2010). A number of studies on LiDAR-derived tree height from both single tree and plot level height measurements indicated the accuracy of the LiDAR between R^2 0.80 - 0.98 (Andersen et al., 2005; Coops et al., 2007; Heurich, 2008; Holmgren & Nilsson, 2003; Lee & Lucas, 2007; Morsdorf et al., 2004). These studies were not undertaken in a tropical rain forest. Therefore, there is a need to establish the possibility of obtaining similar accuracies in the tropical forests with diverse species and mixed canopy. Study carried by Srinivasan et al., (2015) used TLS and carried out field measurement using the True Pulse with report R^2 of 0.92 and RMSE of 1.51 m for the tree height.

The accuracy of tree heights measured from Airborne LiDAR may be affected by a number of factors. For example; size and reflectivity of the tree, shape of the tree crown, LiDAR pulse density and footprint or pulse diameter (Edson et al., 2011). However, the outcome is still more accurate than the field measurements. This is still used in most biomass estimation models and allometric equations. The sensitivity of the tree error associated may yet have a significant effect on the amount of AGB and carbon estimation.

Chave et al., (2005) reported that, allometric equations based on tree height and DBH gave highly accurate estimation of above the ground forest biomass in a study that was carried across the tropical rainforest with diverse species of approximately 300 tree per hectare. This study considered individual tree data that was collected over a period of time, and it did not obtain the tree height from either Airborne LiDAR or TLS. Tree height data was mainly collected using clinometers. This would be similar to the situation in the study area of Roland et al., (1999) who reported that the tree density in Ayer Hitam Forest reserve was 210 - 366 tree per hectare with diverse species. However, the current study is mainly focused on the use of ALS and TLS to measure the tree height as well as the Leica DISTO field measurement equipment which have better accuracy than the clinometer (Bragg, 2008; Clark et al., 2000; Lois, 1998).

Zawawi et al., (2015) **o**bserved that forest type is one of the determinant factor of accuracy of tree height measured from airborne LiDAR and TLS as well as data resolution in ensuring the accuracy of tree height measurement. Meanwhile, Andersen et al., (2006) reported very high accuracy of measuring tree height in a forest composed of Douglas-fir (*Pseudotsuga menziesii*) and Ponderosa pine (*Pinus ponderosa*) using a TLS and total station survey. This needs to be carried out in a tropical rainforest setting with multipole layers, massive understory and different conditions as opposed to where these studies have been done.

Kwak et al., (2007) concluded that LiDAR data can be effectively used for forest inventory, particularly for identifying individual trees and estimating tree heights. The study was performed to delineate specific trees, where extended maxima transformation was used with the morphological image-analysis method, and then estimate the tree height from the Airborne LiDAR data. This needs to be investigated if it can give the same related result with an improved accuracy in a tropical rain forest with various tree species as well as dense understorey.

Andersen et al., (2006) also reported high accuracy of tree height measurement when Airborne LiDAR of narrow-beam (0.33 m), high density of 6 points/m² was used. The same study provided a summary of height measurements from Airborne LiDAR that resulted in high and acceptable accuracies when Airborne LiDAR height was validated using high accuracy field measurements (Table 2-3)

Table 2-3: Summary of the results of previous LiDAR-derived tree height measurements

Species type	Location	Density	Field Height estimation method	Field Height Lidar Relationship	Reference
Leaf-off deciduous	Eastern UK	5	Total station survey	Mean = -0.91 (shrub)	Gaveau & Hill (2003)
Norway spruce (S), Scots pine (P), birch (B)	Finland	5	None	Mean ± SD = -0.20 ±0.24 (P), -0.09 ±0.81 (S),-0.09 ±0.94 (B)	Yu et al. (2004)
Douglas-fir, Western hemlock	North-western US	4	Impulse Handheld laser	Mean ± SD = 0.29 ± 2.23	McGaughey et al. (2004)
Norway spruce, scots pine	Finland	24	Tacheometer	Mean =-0.14; RMSE = 0.98	Hyyppä et al. (2001)
Leaf-off deciduous	Eastern USA	12	Laser rangefinder & Clinometer	RMSE = 1.1	Brandtberg et al. (2003)
Scots pine	Finland	10	Tacheometer, theodolite-distometer	Mean ± SD = -0.65 ± 0.49	Maltamo et al. (2004)

Sources: Adopted and modified from Andersen et al., (2006) The studies listed in Table 2-3, used Airborne LiDAR and assessed its accuracy using highly accurate field height measurement systems, therefore, the accuracy of the height after validation was relatively high. On this basis using Airborne LiDAR to validate tree height measurement would offer much better AGB estimation accuracy. Most of the studies indicated in the Table 2-3 were not carried in the tropical rain forest, therefore, this aims at investigating using the Airborne LiDAR in a tropical forest setting with different condition to the ones reported.

Király et al., (2007) used TLS to carry out a survey in forest reserve 46 located in Austria, two methods were applied for estimating tree height. These methods include cluster method and crescent moon method where tree stems are modelled to measure the tree height. The two methods were successful and the accuracy of the two methods were comparable. The use of TLS in Ayer Hitam forest reserve, would be interesting given the different forest types. This will be a tropical rain forest region compared to Austrian forest reserve 46, which is mainly temperate. The focus in this study is to obtained the 3 D view of the tree and obtain the tree height using the measurement software for tree height.

To date a number of studies have done sensitivity analysis of errors associated with biomass and carbon estimation using ALS, TLS and field measurements most notably (Disney et al., 2010; Ene et al., 2012; Frazeret al., 2011; Heath & Smith, 2000). However their focus has been on the errors in co-registration of LiDAR data, model based descriptive inferences of parameters, identification of best parameters influential in uncertainties in carbon budget as well as LiDAR return. This study will focus on simulation and sensitivity of the tree height measurement errors from remotely sensed data to field measurement on the estimation of AGB and carbon stock.

Chave et al., (2004) reported a number of errors associated with estimation of AGB, these involved the measurement of DBH and tree height with an uncertainty of 47% of the estimated AGB due to allometric and measurement uncertainties. In the same study, different allometric equations estimated the AGB between 214 Mg ha^{-1} to 461 Mg ha^{-1}, with a mean of 347 Mg ha^{-1}, this potentially indicated the error in the various estimations. Some errors are also associated with the sample plot size as well as the landscape-scale variables (Chave et al., 2003). This study was focused on errors associated with tree height only and assessing how sensitive AGB and carbon stock are to changes in height due to errors.

Ginzler & Hobi, (2015) used vertex ultrasonic hypsometer to measure tree height and assessed the accuracy using CHM derived from stereo images and image matching in Switzerland with mountainous terrain with forest mainly composed of deciduous and coniferous forest. The accuracy assessment of the DSM was done using topographic points of the Swiss national topographic survey with an absolute accuracy of 3 to 5 cm, from the 3 D matched images, a 1 m resolution DSM was created and consequently a CHM. The results show that there was an acceptable correlation ranging between 0.6 - 0.83 for high and low elevations respectively. The use of CHM from stereo images offers the basis to use CHM from Airborne LiDAR which offers more accuracy compared to the image matching.

3. MATERIALS AND METHODS

3.1. Materials

3.1.1. Study area

The study was done in Ayer Hitam tropical rain forest reserve, Selangor, Malaysia. The Ayer Hitam forest is situated in the southern edge of Kuala Lumpur City, Malaysia approximately at 3º 01´29.1"N 101º38´44.4"E. It covers around 1248 hectares of pristine rainforest and consist of mainly tropical rain forest tree species. The altitude in the forest ranges between 15 meters to 233 meters above sea level (Nurul-Shida et al., 2014). It is one of the oldest tropical rainforest. According to (UPM, 2015), the forest is the only lowland forest that exists naturally within Klang Valley and Putrajaya area.

It is a unique forest due to the fact that it has maintained the history of Orang Asli community. It also documented the history of the Second World War. The forest reserve is also attractive due to the geological make-up of exciting soils and land formations. Figure 3-1; shows the study area location map.

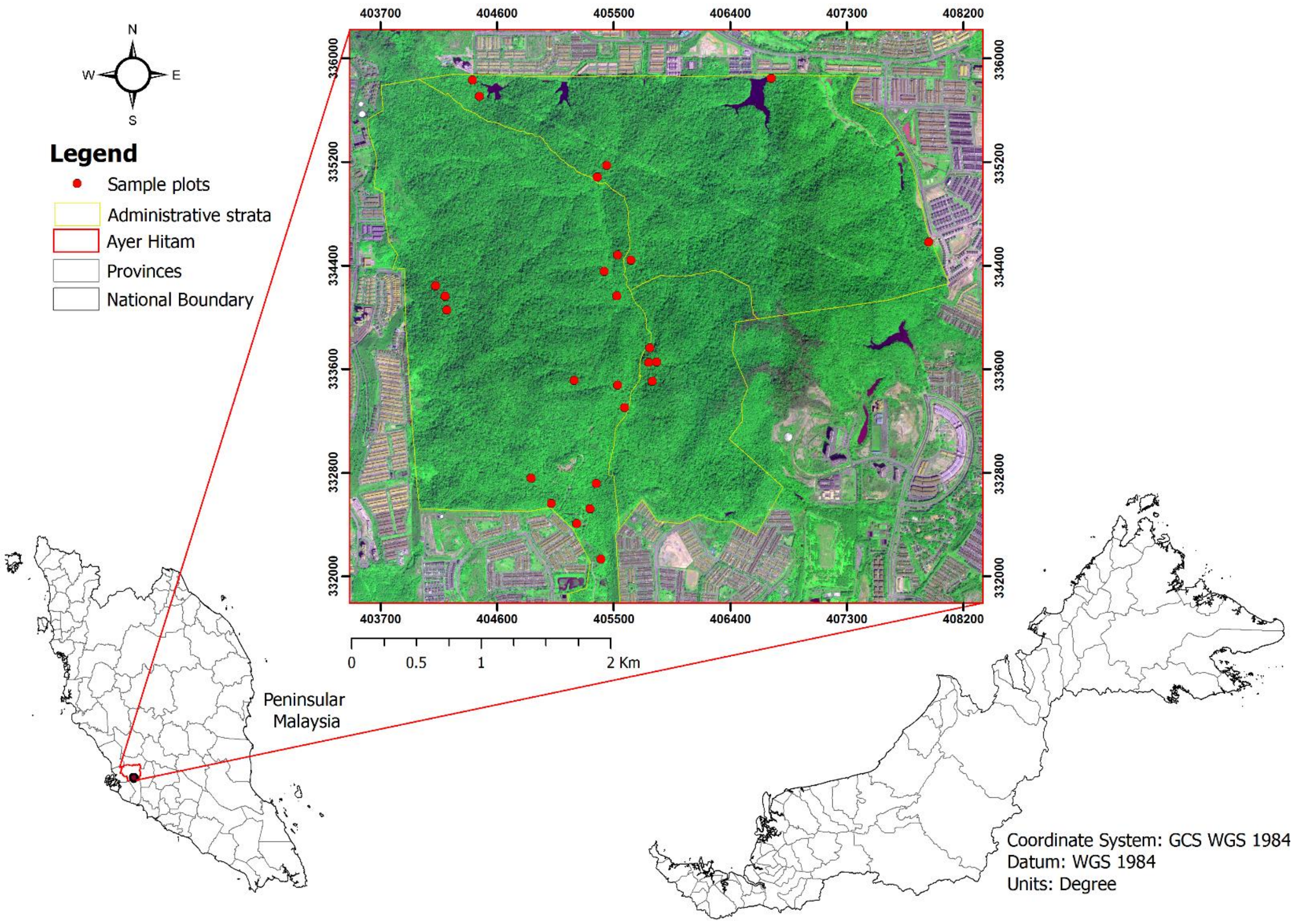


Figure 3-1: Study area location map with sample plots

3.1.2. Climate

Ayer Hitam tropical rainforest is characterised by tropical monsoon climate with temperatures that range between 23 °C to 32 °C, an average annual rainfall of 1,765 mm with the peak been between October and February (Toriman et al., 2013). It is characterised by relatively humid tropical condition.

3.1.3. Vegetation and Other Species

The study area is a tropical rainforest that is recognized as one of the oldest lowland rainforest. The forest was selectively logged many times from 1936 to 1965. It holds approximately 430 species of seed plants as well as 127 timber producing species of trees (Ibrahim et al., 1999). Approximately 100 species of plants in the forest are medicinal, it also contains at least 40 species of fern and their allies, 43 species of moss diversity. Other diversity of plants comprise of rattans and orchids which are mainly of economic and ornamental value. The forest also contains endemics and rare species (Fridah & Khamis, 2004).

The study area possesses approximately 197 species of fauna (UPM, 2015). With the receding size of the forest, larger mammals have disappeared or reduced in number especially tiger that was sighted in the forest no longer exists. Other mammals that exist include the wild boars and mousedeers (Fridah & Khamis, 2004). The forest also harbours 160 bird species mainly frugivorous and insectivorous, migratory birds such as Siberian Blue Robin (Mohamed & Abdul, 1999).

3.1.4. Data

In this study, various datasets were used, these include; Airborne LiDAR data, TLS data as well as the field measurements. The Airborne LiDAR data used was acquired by the University Putra Malaysia (UPM), for the purpose of their on-going forest inventory activities. The LiDAR data was collected with approximately 5 – 6 points/m^2 with Orthophoto. The data was used for the derivation of Canopy Height Model (CHM) from the Digital Surface Model (DSM) and Digital Terrain Model (DTM) in this study.

Other data sets for the study include: Tree height and DBH measurements collected from the field in Ayer Hitam Forest and point clouds (multiple scans) from TLS from a total of 26 sample plots.

3.1.5. Field instruments

Various field instruments and equipment were used to measure forest inventory parameters. Field instruments used for the study include: RIEGL VZ-400, iPAQ, GPS, Leica DISTO 510, Diameter tape (5 meters), Measuring tape (30 meters) and data recording sheet. The details of field instruments and their uses are given in Table 3-1.

Table 3-1: List of instruments and image used in field for data collection

Instruments	Purposes/Use
RIEGL VZ-400	Terrestrial laser scanning
Mobile Mapper 6	Navigation and positioning
Leica DISTO D510	Tree height measurement
Diameter tape (5 meters)	DBH measurement
Measuring tape (30 meters)	Plot delineation
Worldview-3 satellite image (Date of acquisition: 12-09-2014)	Sample plot identification
Suunto Clinometer	Bearing and slope

3.1.6. Software

During this study, different and various software packages were used for processing and analysis of datasets. This ranges from the field, TLS and Airborne LiDAR datasets. Table 3-2; shows the software packages and the purposes or use.

Table 3-2: List of software and purpose of their use

Software	Purposes/Use
ArcGIS 10.2.2	GIS and Mapping tasks
ENVI Suite/ERDAS Imagine 2015	Image processing/Airborne LiDAR data analysis
RiSCAN PRO	TLS data processing
CloudCompare	Slicing, cylinder fitting, manual measurements
CompuTree	Creating digital terrain model, automatic DBH measurement
LP360	Airborne LiDAR data processing
LasTools	Airborne LiDAR data processing
R Studio	Statistical analysis
SPSS	Statistical analysis
MS Office 2013 (Excel)	Statistical analysis
MS Office 2013 (Word)	Reports and Thesis writing

3.2. Methods

The method of this study comprised of mainly four (4) parts. The first component was field data collection which involved observation and measurements using field instruments especially Leica DISTO 510 for tree height measurement and DBH using the diameter tape.

The second part of the study involved the use of TLS in various sampled plots for tree scanning (point clouds) and processing of the point clouds, from the processed TLS data, tree height and DBH were measured.

The third component of the study involved processing and measurement of tree height from the Airborne LiDAR CHM. The measured tree height from field, TLS were validated using the height measurement from Airborne LiDAR CHM, the errors associated with field measurement and TLS were quantified during the accuracy assessment. Calculation of AGB and carbon stocks was done using the validated actual height measurements from field, TLS and Airborne LiDAR.

The fourth part of the study involved the sensitivity analysis of the AGB and carbon stock to changes or variations in tree height measurement due to the errors associated with the methods. Tree height measurements for the different methods were varied by the standard errors quantified from the accuracy assessment, the height adjustments were done by adding or subtracting the threshold based on the errors from field and TLS height measurement. Figure 3-2, shows the detailed flow chart for the methods/processes and outputs for this study.

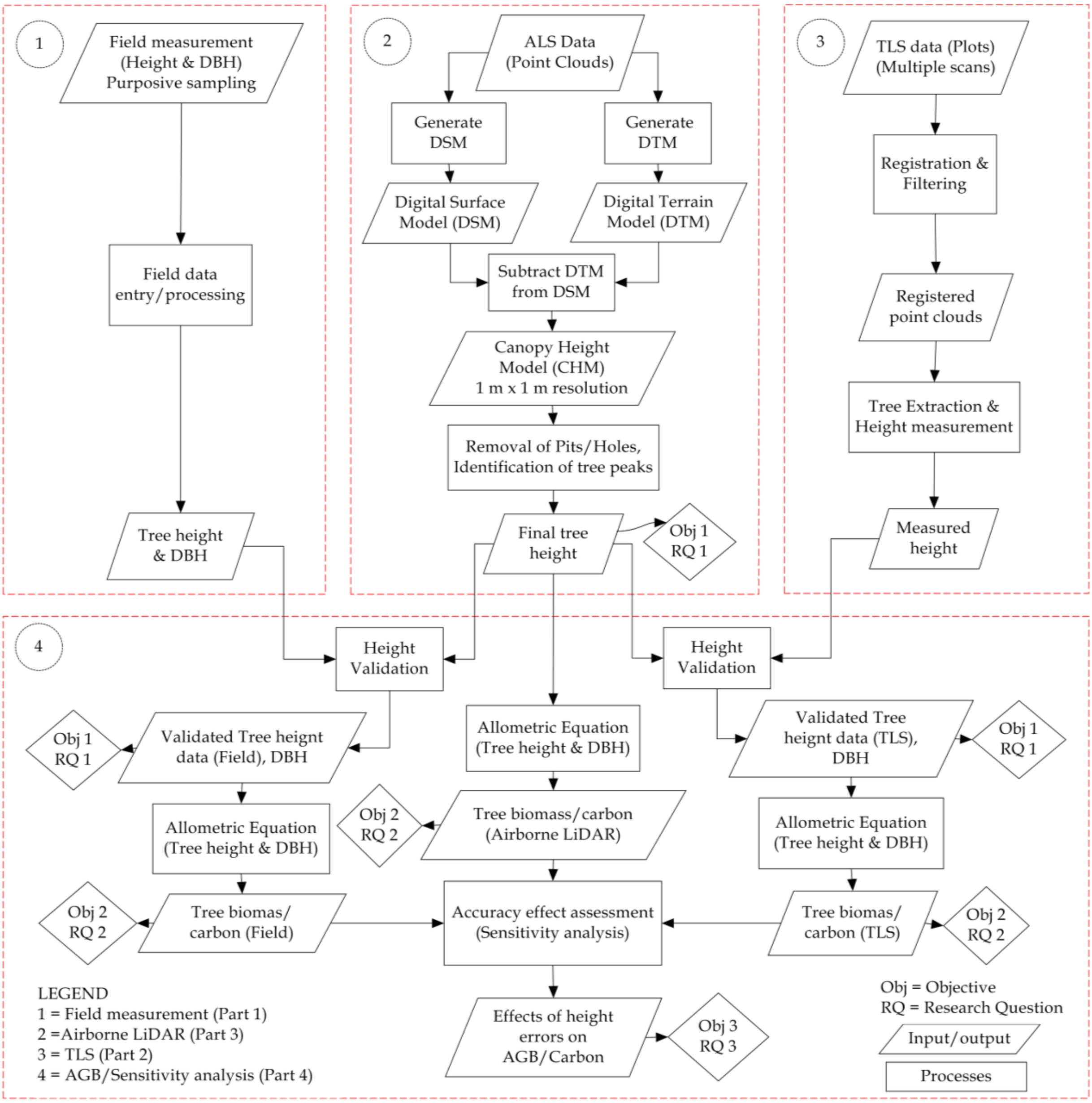


Figure 3-2: Flowchart showing the methods used in the study

3.2.1. Pre-field work

A number of activities were carried out before the field work for this study. These involved; design of field record sheets (Appendix 5), testing of the instruments to be used in the field as well as understanding the conditions in the site, identification of the data needs especially relevant data to be collected from the field and the tools and methods required to collect the data.

3.2.2. Plot size

Circular sample plots of 12.62 radius in flat terrain was used. The area of each plot was 500 m² (0.05 Hectare), with tree diameter equal or more than 10 cm only measured based on the amount of biomass they would contain (Brown, 2002). A plot size of 500 m² was used due to its effectiveness in capturing sufficient number of species and uniformity with the previous data collection (Neldner & Butler, 2008). A slope correction was done in areas with slope that was significant to affect the plot size so that the plot size in areas that were sloppy were as the same size as the flat sample plots using the slope correction table (Appendix 4). Figure 3-3 shows an example of the circular plot that was done during the field work with radius of 12.62 m.

Figure 3-3: Plot size (12.62 m) with the trees and its boundary
Source: Adopted from Asmare (2013)

3.2.3. Sampling design

In this study, purposive sampling approach was used, based on the terrain orientation, stand density (Otukei & Emanuel, 2015), most of the study area was in accessible and rugged. The samples were selected based on the elevation, an existing strata based on the administrative setup of the study area by the University Putra Malaysia (UPM) and the tree stand density. As a lowland tropical rainforest, the purposive plots were distributed in the administrative strata where it was possible to carry the TLS equipment that was also heavy approximately 30 kilograms with the camera. Samples were also selected from areas with less undergrowth as there was need to slash to reduce occlusion of the tree stems by the undergrowth. A total of 26 plots were sampled as shown in Figure 3-1 within the 3 strata each with 500 m^2 size.

3.3. Data collection

3.3.1. Biometric data collection

Field data was collected between September and October 2015. The manual measurements of tree height, DBH were conducted using the various field instruments. The GPS coordinates of the centre of the plot was measured with mobile mapper GPS. A diameter tape was used to measure DBH. In addition, other important observations like slope and bearing were noted. Field measurement/tree parameters mainly; tree height was measured from the circular plots of 12.62 m (Figure 3-3) radius using the Leica DISTO 510. DBH for trees in the plot were measured especially the trees with diameter greater or equal to 10 cm were measured using diameter tape at the 130 cm above ground (Chave et al., 2005). A DBH stick was used to accurately measure DBH at 130 cm from the ground to ensure consistency. TruPulse distance range finder could not be used in the study area due to difficulties in observing the bottom and top part of tree without occlusion from other trees. The field data was entered in to Microsoft office (excel) for further analysis and processing during the post field work activities.

3.3.2. TLS Scan Registration

The TLS scans were downloaded from the scanner using the RiSCAN Pro software. The point cloud data obtained from the multiple scan positions in the sampled plot were registered to central scan position to form the 3D of the plot. Individual trees extracted.

3.3.3. Plot delineation

Locating central position after identification of plot, the centre of the plot was established in a position where there was minimum occlusion in the scanning. The reference/home scan was carried out from the central part of the plot (Wezyk et al., 2007) and the three other scans carried out of the plot placed in an angle of 120° determined using the TLS tripod stands to each other in a convenient location due to the elevation of the plots. 12 Cylinder reflectors and 4 Circular reflectors placed with then the plot, the reflectors were used for registration and georeferencing of the multiple scan positions in a plots (Figure 3-4).

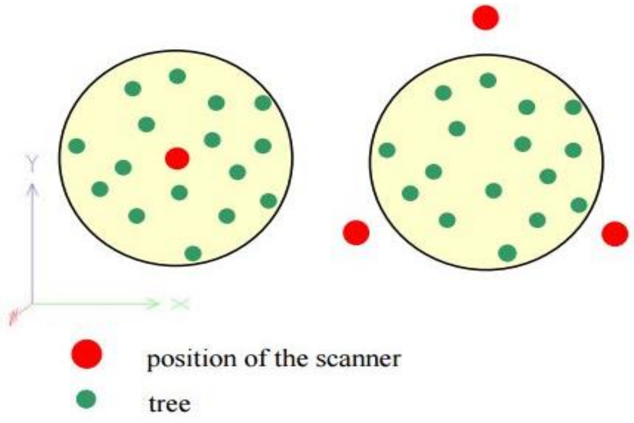


Figure 3-4: The positioning of the TLS in a plot with the multiple scan positions
Source: Adopted from Bienert et al., (2006)

3.3.4. Preparation

Preparation of the plots before scanning was required. Most of the plots had dense under growth, therefore, clearing in the line of the reflectors was done in order to ensure that the reflectors were visible and registered by the TLS from the home scan for the cylindrical reflectors as well as the circular reflectors (Bienert et al., 2006a). Then the trees with the plot with DBH equal or greater than 10 cm were marked and numbered using tags that were printed and laminated with the numbers.

3.3.5. Setting TLS and Scanning.

The TLS was placed on the identified scan positions, setting of the instrument was carried out to ensure the levelling of the instrument with roll and pitch with the scanner own coordinate system (SOCS) that was used in the field. The SOCS offers the relative coordinate system of the scanner. New scan positions within the plot were established to form the 3 Dimensional view of the plot from the multiple scans.

The scanner was set to collect data in full waveform with Panorama 60 resolution as well as acquisition of eight overlapping digital images that later were used to colour the point clouds. The system was set to carry out fine search and registration of the reflectors, the reflectors were later used for the identification and registration of the scan positions. Then the point clouds for each scan position were obtained in 2 Dimension (Figure 3-5). The tree numbers can be viewed clearly on the coloured 2 Dimensional view of the plot.

Figure 3-5: 2D view of a scanned plot in true colour (Scan position 1, Plot 14)

3.4. Data Processing

3.4.1. Biometrics data

The field data collected were entered in to an excel sheet, mainly the GPS coordinate data of the centre of the plot and selected trees within the plot, tree height, DBH, plot radius among others. A total of 799 trees were measured within 26 plots where Terrestrial Laser Scanning was also done. The scan positions were noted with bearing of the second scan position after the first scan position which was mainly the central scan position. Geotagged photographs were also taken from the field for the labelled trees within the plot.

3.4.2. Pre-processing/Registration of TLS scan positions

RiSCAN PRO version 2.1 software was used for downloading and converting the data obtained from the Terrestrial Laser Scanner. Coarse registration of the various scan positions were done with 15 tie points using the reflector scans and the three outer scans to the plot were registered to the central plot. Multiple station adjustment (MSA) of the multiple scans to form the 3D view of the plots was undertaken for all the 26 sampled plots. The MSA with high accuracy were obtained for the 26 plots with standard deviation of the point clouds less than 0.02 m for all the plots (Table 3-3) and Figure 3-6 indicating the normal distribution of the point clouds for plot 11.

Table 3-3: Multiple scan position registration and accuracy in standard deviation (Std. Dev.)

Plot	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Std. Dev. [m]	0.0185	0.0162	0.0200	0.0153	0.0160	0.0138	0.0149	0.0140	0.0201
Plot	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*
Std. Dev. [m]	0.0149	0.0127	0.0146	0.0163	0.0157	0.0206	0.0177	0.0224	0.0155
Plot	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	
Std. Dev. [m]	0.0179	0.0195	0.0163	0.0158	0.0184	0.0148	0.0169	0.0158	

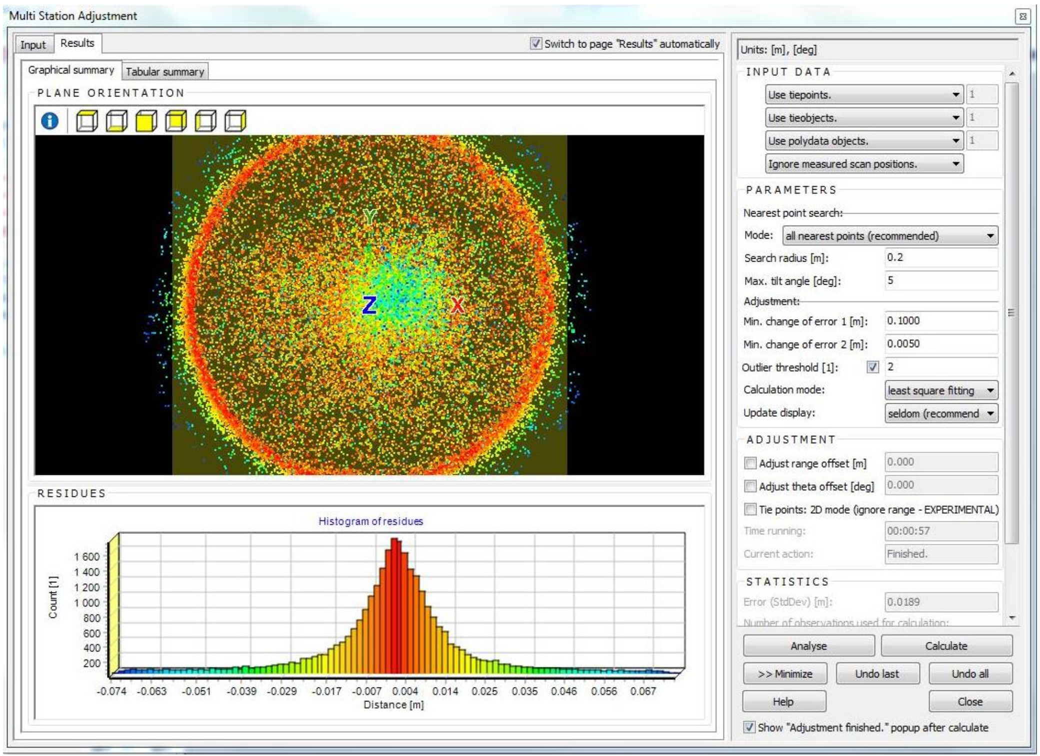


Figure 3-6: Multi Station Adjustment of the registered scan positions (Plot 11)

3.4.3. Plot/Tree extraction

The registered and georeferenced plots were then filtered and polydata was created from the point clouds. In this process, all the points inside the area of interest (within the plot radius) were extracted for individual tree detection and extraction process. This process also ensured delineation of the plot boundary. A cylinder of radius 12.62 m (sample plot radius) was used to filter the points outside the plot using RiSCAN Pro software. The filtered point clouds were then used for detection of trees from which the DBH and height were measured.

During the field work, all trees were tagged with a number, the numbers were used to identify the individual trees when the point clouds were displayed in true colour or linear reflectance. The selection tools in RiSCAN Pro software were then used to select the individual trees from the point clouds, delineate and extract the trees using the panoramic and eight overlapping photographs that were taken from the field using the camera that was mounted on the scanner. The scan photographs were also used to colour the point clouds as well as verification of the extracted trees with numbers.

The extracted trees were saved as polydata in the RiSCAN PRO software, which can then be exported to the CloudCompare software for the automatic height measurement as indicated in Figure 3-7 by fixing a box or a cylinder around the extracted tree.

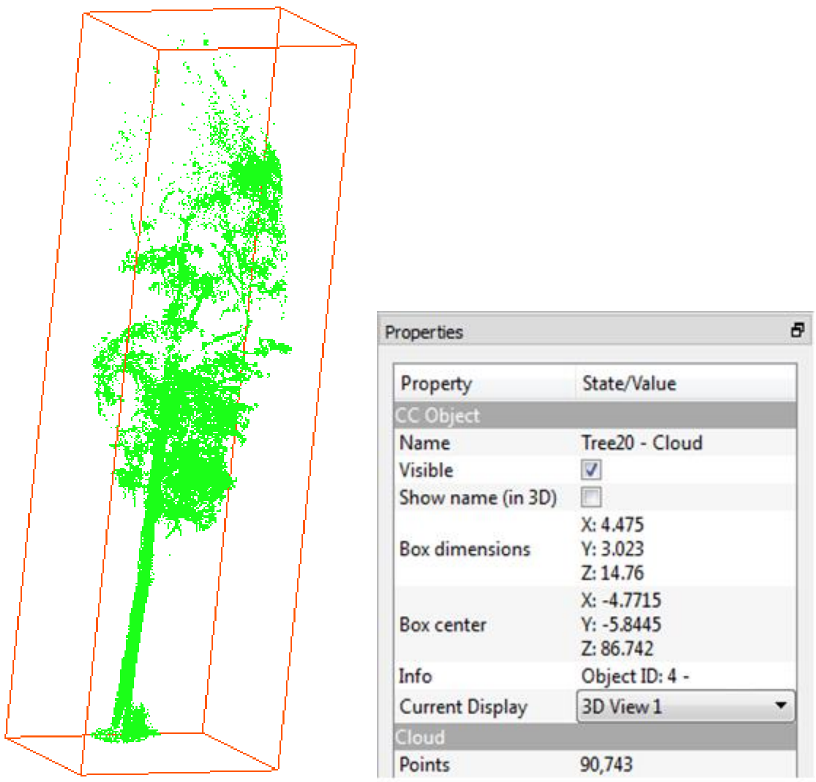


Figure 3-7: Tree height measurement using box/cylinder method (Tree No. 20, Plot 10)

The Box/cylinder method in CloudCompare software picks the top most point in the point clouds as well as the bottom and defines the height when the 3D tree is fit in a box or cylinder. The Box dimensions are defined by the size and distribution of the point clouds.

The manual measurement allows accurate height measurement as the compared to the box fitting where automatically the top most and bottom point clouds are considered as the height of the tress after the extraction from the RiSCAN Pro software. The tree height and DBH were then measured in the RiSCAN Pro (Figure 3-8). This method has been proven accurate by (Prasad, 2015a) who compared it with automatic measurement.

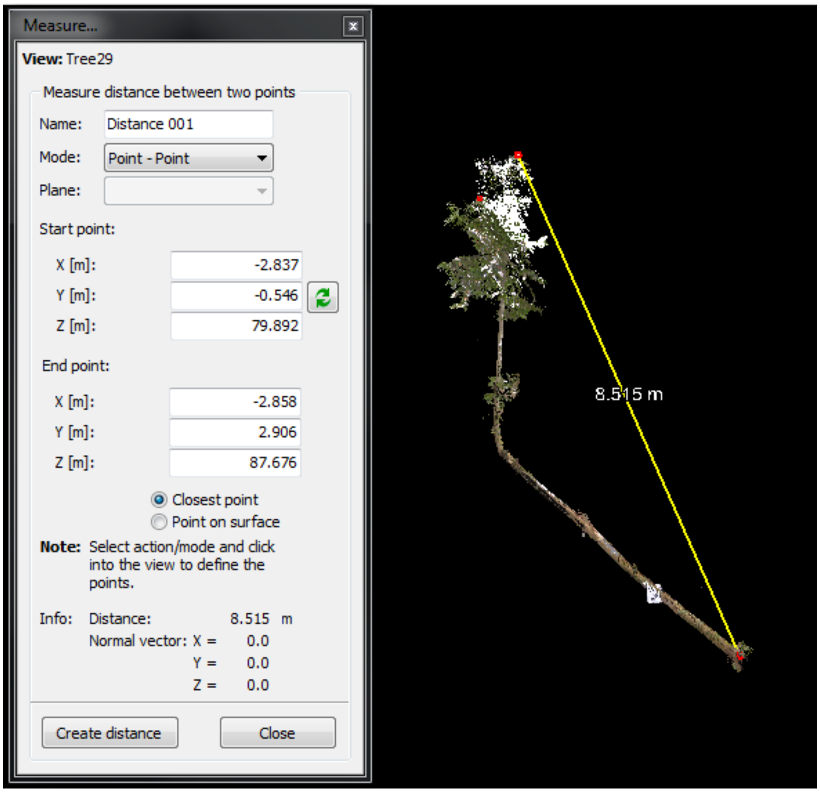


Figure 3-8: Tree height measurement using RiSCAN Pro software (Tree No. 29, Plot 16).

3.5. Airborne LiDAR data

The airborne LiDAR data that was used in this study was obtained from University Putra Malaysia (UPM). The data was acquired with LiteMapper 5600 system with the parameters summarised in Table 2-1. The data was collected on July 23, 2013 with WGS 1984 UTM Zone 47N reference system. The point cloud data with xyz information was obtained and converted to Las files from the xyz format using the LP360 tools. The LP360 is an extension to ArcGIS software that allows visualization and processing of very large point clouds (LIDAR and dense image matching) in a desktop GIS environment. It provides tools from rapid visualization and derived product generation through advanced features such as automatic ground classification and footprint extraction. The tool is designed and developed by the QCoherent software LLC Company. (QCoherent, 2016).

The Airborne LiDAR point clouds in Las file formats were then processed in the LasTools software. The LasTools software contains various algorithms and tools that can be used for processing LiDAR data (rapidlasso GmbH, 2016). The tools and algorithms in LasTools that were used to process the Airborne LiDAR data include; LasInfo, LasView, LasTile, LasGround, LasHeight and Las2Dem among others. LasView algorithm was used to view the point cloud data. LasInfo tool was used to extract the detailed information about the properties of the data that was obtained, the point density and the spatial reference information. The LasGround Algorithm was also used for the bare earth extraction (DTM) where by LiDAR points were classified in to ground points (class 2) and non-ground points (Class 1). The classified point clouds from the LasGround algorithm were then further classified to generate height using the LasHeight for the computation of each point above the ground.

The LasHeight tool was then used to generate DSM based on the LiDAR point classifications to compute the height of each point above the ground. The DTM and DSM were triangulated using Las2Dem tool in to a 2 Dimension raster format mainly a TIFF format. The DTM and DSM were used to produce the Canopy height model (CHM). In order to avoid quantizing and clamping, replace-z setting was done in the LasHeight where the z values were replaced with the height information (rapidlasso GmbH, 2016) hence dropping points with zero z-value as the ground. Las2Dem algorithm was then used to generate the standard canopy height model (CHM) with 1 m cell size based on the number of points/m^2.

The standard CHM contained pits and holes. Therefore a pit/hole cleaning of the CHM was done using the pit free algorithm (Khosravipour et al., 2014) as shown in Figure 3-9. Based on the measured tree height from the field, the Airborne LiDAR point clouds with height below zero (0 meters) were dropped and those with height values above 50 meters were also dropped.

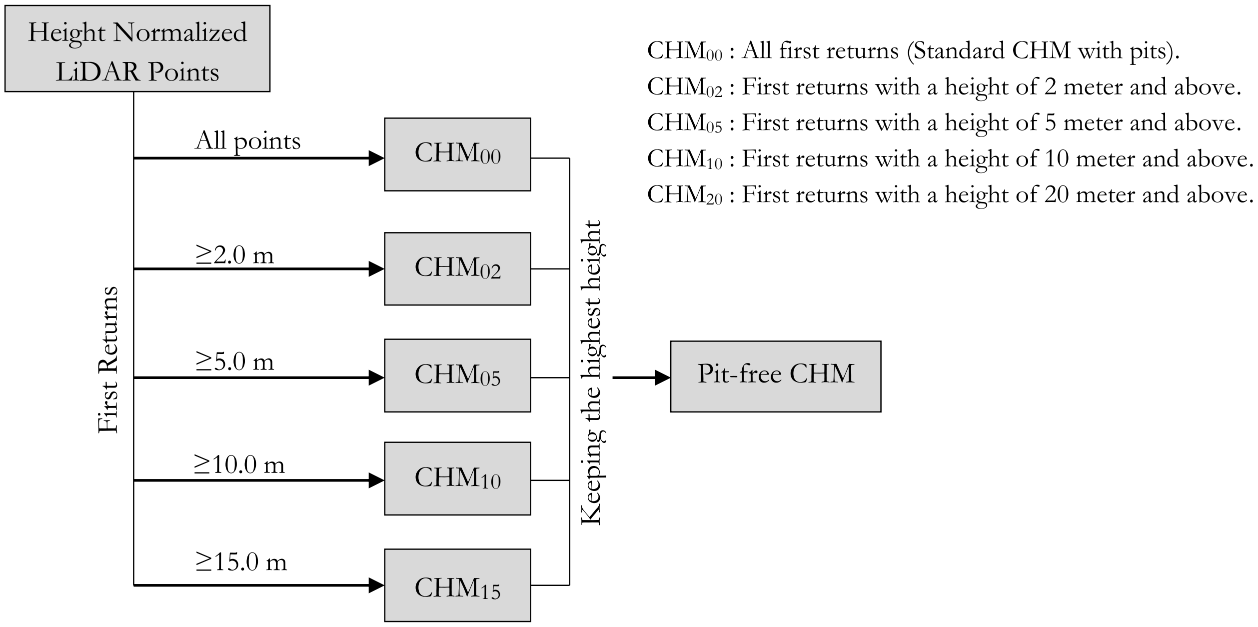


Figure 3-9: Pit free algorithm for CHM.
Source: Adopted from Khosravipour et al., (2014)

The pit free algorithm in Figure 3-9 was used to create a noise free CHM with height values using the Las2Dem algorithm in the LasTools, with various level of triangulation. The pits and noise were removed using the pit free algorithm. The effectiveness of this algorithm was tested by comparing it with the Gaussian filter (Khosravipour et al., 2014).

3.5.1. Segmentation and Feature Extraction

The pit free CHM was segmented using the eCognition software to delineate the crown of the individual trees visible on the airborne LiDAR based on the object oriented approach which focuses on colour, shape, texture, size. A number of parameters were set especially the multi-resolution segmentation, watershed transformation, tree morphology in a rule set that was used on a subset and later applied to the whole study area CHM, and the accuracy assessment was carried out in order to obtain an individual tree identification and matching.

Single tree objects were detected, the individual tree detection method has been intuitive as indicated by (Yao et al., 2014) that offered better results compared to area based method. Manual delineation and extraction of trees was carried out using the field collected samples as well as segmentation (Equation 3-1 to 3-3). Trees were identified using the number tags from the TLS data, bearing and the location of the multiple scan positions and the corresponding trees were also delineated from the Airborne LiDAR and their height measured. Tree features were extracted as points from the observed crowns and matched with the field data as well as the TLS data.

Equation 3-1: Computation of over segmentation

$$Over\ segmentation = 1 - \frac{area(xi \cap yj)}{area(xi)}$$

Equation 3-2: Computation of under segmentation

$$Under\ segmentation = 1 - \frac{area(xi \cap yj)}{area(yj)}$$

Where;

xi	Reference Polygons manually delineated crowns
yj	Set of segments results from segmentation

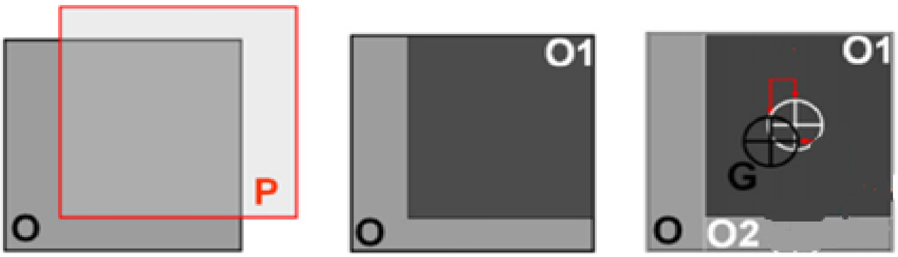
Equation 3-3: Measure of closeness

$$D_{ij} = \sqrt{\frac{Oversegmentation_{ij}^{2} + Undersegmentation_{ij}^{2}}{2}}$$

Where;

D is the segmentation goodness

The segmentation accuracy was assessed using the visual techniques (Möller et. al, 2007) commonly known as the relative area approach to validate the CHM segmentation by using the reference polygon of the manual digitization of the known and identified trees on the Airborne LiDAR CHM (Figure 3-10).



a) Overlap b) Containment c) Containment & Difference between the object centres (G)

Figure 3-10: Topological & geometric relationship for the segmented and the reference polygons.
Source: Adopted and modified from Möller M. et al., (2007)

The Object Based Image Analysis (OBIA) approach was adopted for the segmentation of the CHM in the eCognition software, to divide tree crowns in to individual trees (Jakubowski et al., 2013), the CHM was first segmented in to coarse objects based on the nature of tree crowns that were observed in the plots during field work and the objects that were likely short trees were surrounded by the ground pixels. Then later improved based on the brightness of the pixels.

3.5.2. Accuracy of the CHM

The airborne CHM derived tree height was considered as the most accurate tree height measurement to validate the field and the tree height obtained from the TLS. Various studies have shown that Airborne LiDAR is very accurate compared to field and TLS measurements (Leitold et al., 2015) with accuracy 0.19 ±0.97 meters when field data was collected using a GNSS solution. Leitold et al., (2015) further indicated that, the accuracy reduces with the footprint size and therefore biomass from such CHM are sensitive to the errors. Andersen et al., (2014) also indicated that Tree height measurements from narrow-beam with a density of 6 points/m^2 LiDAR were more accurate with reported mean error ± SD = –0.73 ± 0.43 m compared to the field data. Table 2-3 also indicates other studies that obtain high height measurement accuracy using Airborne LiDAR and high precision ground truth measurement instruments.

3.6. Tree Detection Evaluation

The tree detection was based on the individual tree level by obtaining the matched tree from field plots with TLS and Airborne LiDAR CHM. In this study 26 plots were sampled for both TLS and Field measurement and a total of 799 trees were measured during the field work, 614 of the trees were detected from the TLS Scans which represents 76.84% of trees detected using the TLS. The trees detected on Airborne LiDAR CHM were based on the already identified TLS trees within the 26 plots. This was mainly due to objective of comparing the accuracy of the various tools for height measurement. A total of 345 trees were identified and matched with the TLS trees representing 56.18%. The main focus of tree identification on Airborne LiDAR was on the top layer of the forest since the tree tops were visible to the LiDAR, despite the fact that, the study area is characterized with multiple tree layers. The tree detection was limited to emergent stems with an expectation that they were visible on the CHM (Hunter et al., 2013).

3.7. Statistical Analysis

Various statistical analyses were done especially the analysis of variance (ANOVA) where single factor ANOVA was done, correlation, regression of the variables involved mainly the tree height measurement from the field, tree height measured using TLS as well as the Airborne LiDAR height. A scatterplot/diagram of the related variables were established in order to see the relationship between tree height measured from the field using the Leica DISTO instrument and the TLS. Field height and Airborne LiDAR height as well as the relationship between the TLS measured height and the Airborne LiDAR height. Analysis of Variance (ANOVA) was used to find out the difference between mean of the variables involved.

Based on the correlation coefficients, a protected t-Test was done between the paired variables to observe and examine if there was significant difference between the paired means.

Regression analysis was done to compare the relationship between the tree height measured from the field, TLS and the Airborne LiDAR derived CHM. The relationship between AGB and carbon stocks was also established using the regression statistics. The Airborne LiDAR height was considered to be more accurate based on the previous studies as shown in Table 2-3. The results of the relationships were then used to assess the accuracy based on the calculated Root Mean Square Error (RMSE) between the variables mainly field height and Airborne LiDAR, TLS height and Airborne LiDAR, and the Field height and TLS. Equation 3-4 was used to calculate the RMSE

Equation 3-4: Equation: RMSE calculation

$$RMSE = \sqrt{\sum_{i=1}^{n} (y_i - \hat{Y})^2 / n}$$

Where;

RMSE	Root Mean Square Error of the Relationship
Y_i	Measured value of the Dependent variable
$\hat{Y}_i$	Estimated value of the dependent variable
n	The number of samples

3.8. Above ground biomass and carbon estimation

3.8.1. Above Ground Biomass (AGB)

The AGB was calculated using a generic allometric equation established by (Chave et al., 2005) which is applicable to mixed tree species (Equation 3-5), this model has also been used in Kalimantan, Indonesia (Asmoro, 2014; Rutishauser et al., 2013) with acceptable results which is a tropical country neighbouring the current study area in Malaysia. The inputs of the allometric equation were the DBH measured from the field, wood density and the validated Field, TLS and Airborne LiDAR measurements. Therefore, AGB was calculated for the three (3) methods using the respective height measurements while keeping field measured DBH and wood density constant. The results were statistically compared for significance. Sensitivity analysis of the amount of AGB/carbon was carried out by adjusting the values of tree height based on the accuracies obtained.

Equation 3-5: Allometric equation (Above Ground Biomass)

$$AGB = 0.0509 \times \rho D^2 H$$

Where AGB refers to the above ground tree biomass (kg); ρ (oven-dry wood over green volume) in g/cm^3 obtained from Global Wood Density (Chave et al., 2009), D representing DBH (cm) and H representing height (m). This equation has been selected due it its wide application in tropical rain forest biomass estimation (Chave et al., 2005) most specifically mixed tree species which is the same case with the study area as reported in (Lepun et al., 2007).

3.8.2. Carbon Stocks

The carbon stock for the tree units were derived from the biomass obtained. Carbon content approximately 50% of the total forest biomass (Houghton, 2005). A conversion factor was used to obtain the amount of carbon for the identified trees. In this study, a value of 0.47 was used based on the IPCC guidelines (IPCC, 2007).

Equation 3-6: Carbon stock from AGB

$$C = B \times CF$$

Where the C represents the Carbon stock (Mg); B representing the dry biomass and CF the fraction of Carbon in the Biomass (0.47).

3.9. Effect of error propagation and Sensitivity Analysis

The errors in tree height measurement were quantified. Sensitivity analysis using scatter plot was implemented as evaluated by various studies (Frey & Patil, 2002; Galvão et al., 2001). The basis of the sensitivity analysis were the tree height measurements, effects of the errors resulting from the different height measurement technologies were assessed. The errors were quantified and the sensitivity of AGB to variability or changes in height measurements and the error associated were done using the scatter plot method of sensitivity analysis.

The height obtained from the Airborne data was used as the base for height measurement error estimation. Then, the field and TLS height were varied to assess the sensitivity and uncertainty associated with the amount of biomass to the changes in the height. How much biomass was lost or underestimated was assessed by comparing the tree heights and assessment of the accuracy. Different height measurements varied by error margin were input in to the allometric equation, then change in the AGB was observed and assessed.

A number of trees were selected to carry out the sensitivity analysis out of the sampled trees from the study area (Calders et al., 2015). The selection of the trees was undertaken to reduce the size of the plots and make them clear and visible to understand the effects on the variation of the tree height to the amount of AGB and consequently the carbon stock.

4. RESULTS

4.1. Field forest biometric data

Forest biometric data mainly tree DBH, Height obtained from field observations were entered in excel sheet. A number of trees based on the number tag were selected based on the detection carried out in both Airborne LiDAR and Terrestrial Laser Scanner data.

4.1.1. Diameter at Breast Height (DBH)

During the field work, 26 plots were sampled, with 779 trees measured with DBH of equal or greater than 10 cm. These plots were also scanned using the TLS. The trees in TLS point cloud data were extracted from the plot and DBH measured. The field measured DBH was used to validate the DBH from the TLS where there was very high correlation coefficient of 0.98 and $R^2 = 0.96$ with RMSE = 0.26 cm (0.96%). The DBH was measured at exactly 130 cm stem height using a DBH 130 cm stick to ensure consistence in the measurements. The distribution of the measurements were tested for normality.

Table 4-1: Summary statistics for the DBH collected

	Field Measured DBH [cm]				TLS Measured DBH [cm]				
Plot No.	Mean	Std. Dev.	Min.	Max.	Mean	Std. Dev.	Min.	Max.	Count
1	23.92	10.42	10	42	23.44	10.47	9.5	42.2	12
2	38.62	35.52	11	150	36.47	24.09	11.2	108.0	13
3	29.30	15.52	11	59	27.73	15.25	10.9	58.8	20
4	30.69	11.60	16	52	30.62	11.73	15.9	52.3	13
5	30.67	17.18	11	69	29.49	16.60	11.3	68.7	18
6	25.81	11.81	10	54	25.83	11.75	10.2	53.7	16
7	20.18	6.66	13	35	20.07	6.70	12.8	34.6	11
8	18.67	9.67	10	42	18.50	9.58	9.5	41.5	12
9	29.08	13.31	12	51	28.85	13.63	11.0	51.0	13
10	19.83	8.71	10	32	20.11	8.82	10.0	31.8	12
11	27.33	11.07	16	56	29.99	15.90	16.4	65.4	12
12	17.59	8.17	10	34	17.76	8.39	10.0	35.3	17
13	22.31	12.17	12	51	22.56	12.70	11.3	50.0	13
14	24.69	14.39	10	65	25.72	13.30	13.8	62.7	13
15	26.19	16.38	10	66	26.59	16.67	10.0	65.0	16
16	27.93	16.68	10	67	28.85	16.27	10.0	61.7	15
17	21.00	5.32	12	27	21.13	5.74	11.4	27.7	8
18	31.57	17.34	12	68	31.35	16.39	14.0	64.0	14
19	38.00	13.82	19	66	37.63	13.79	19.0	65.6	12
20	35.64	19.09	15	85	35.64	19.09	15.0	85.0	14
21	30.50	12.78	12	54	30.33	12.62	11.9	55.0	12
22	29.85	11.41	20	50	29.15	11.20	19.8	50.5	13
23	26.00	11.68	12	53	26.27	11.70	13.2	53.7	13
24	36.73	15.11	10	71	36.41	15.87	10.3	75.0	11
25	27.64	18.37	10	72	27.27	18.60	10.0	73.2	11
26	23.55	13.29	11	57	23.25	13.12	11.0	56.5	11

The distribution of the DBH by plot was evaluated by establishing the average DBH from field and TLS by plot and the result (Table 4-1) was further plotted in a multiple bar graph that shows the mean DBH measurements by plot (Figure 4-1).

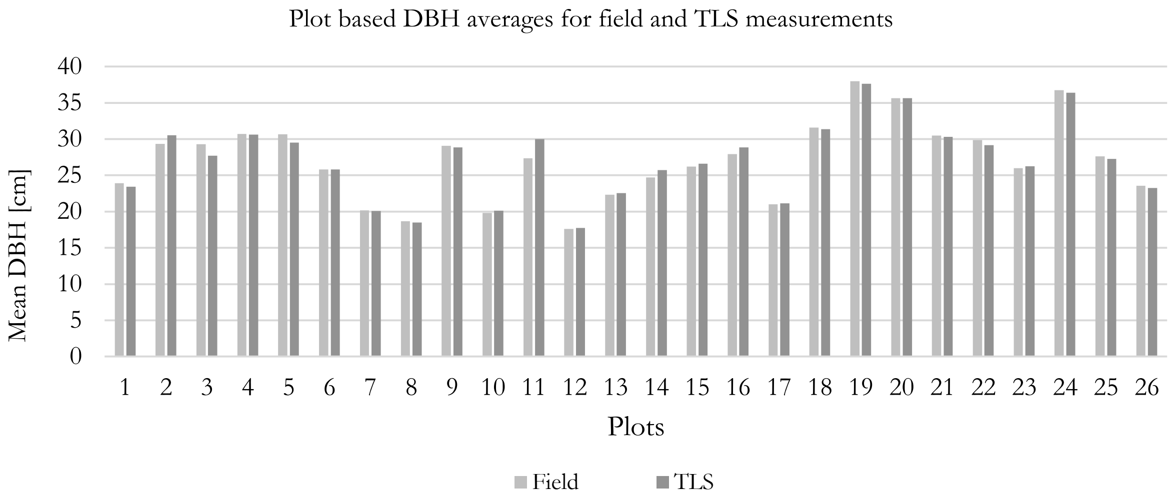


Figure 4-1: Plot based mean DBH distribution of trees for field and TLS.

Validation of the DBH was done using the relationship between field and TLS measurements. Field DBH was used as the independent (*x*) variable while the TLS DBH was use as the dependent (*y*) variable to assess their relationship. The DBH measured from the field was then used as an input to the allometric equation that was used for calculating the individual tree AGB and consequently carbon stocks.

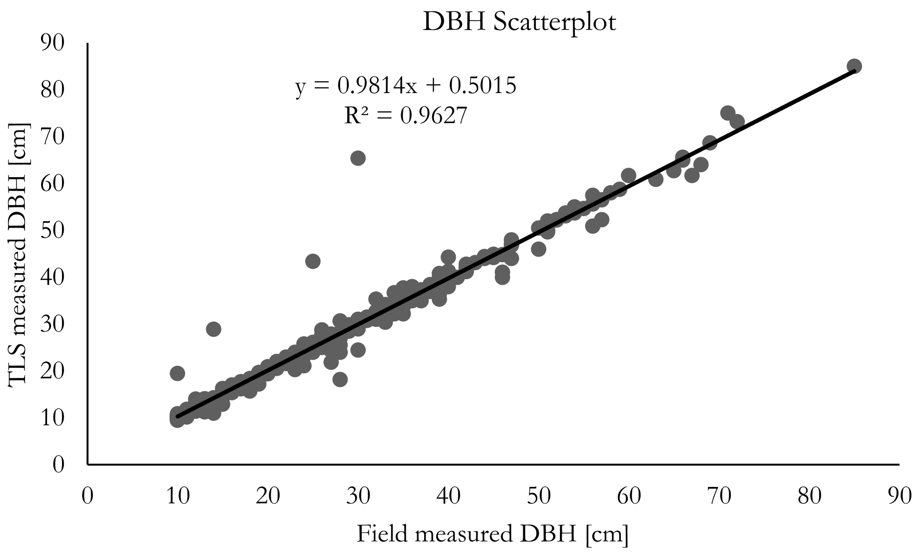


Figure 4-2: Scatter plot for field DBH and TLS DBH.

The result in Figure 4-2 revealed that the R^2 was 0.96 with 0.98 correlation coefficient when field DBH was plotted against the TLS measured DBH.

4.2. Tree Height Measurement

Tree height was measured using mainly 3 different instruments, namely the Leica DISTO 510, Terrestrial Laser Scanner (TLS) and from the Airborne LiDAR CHM. Table 4-2 and Figure 4-9 shows the mean height per plot from the different instruments used. The tree height in Table 4-2 are for the trees that were measured from the field, detected and extracted from the TLS scans as well identified and matched on the

Airborne LiDAR CHM. The tree height measurement were normally distributed from all the 3 measurements. These trees were identified using the tree number tags in the plot (Figure 4-3) and the GPS coordinates, the relative location within the plot that was scanned using the TLS. The direction and the distance of a particular tree was measured on both the TLS 3D view of the plot in RiSCAN Pro software and then matched on the CHM using the 4 TLS scan positions as presented in Figure 3-4.

4.2.1. Field tree height measurement

Field tree height measurement was done using the Leica DISTO 510 laser distance meter. All trees within the plot with DBH equal or greater than 10 cm were measured. In total 799 trees were measured during the field work within the 26 plots. For this study 345 trees were detected on the Airborne LiDAR CHM out of the 614 trees that were detected and extracted from the TLS scans. Table 4-2 and Figure 4-9 show the summary of the tree height measurement using the three different height measurement instruments per plot. With the trees labelled and geotagged photo graphs taken to aid the identification and matching process. Figure 4-3 shows tree number tags during the field measurement and scanning using the TLS.

Figure 4-3: Tree No. 22 DBH and Crown (Plot 16)

4.2.2. TLS derived height

The TLS scan data for the plots were downloaded from the scanner and registered to one common principal scan to form the 3 Dimensional view of the plots. 26 plots that were scanned from the field were all registered with minimal possible accuracy of <0.02 m (Table 3-3) after undertaking Multiple Scan Adjustment in the RiSCAN Pro software with normal distribution of the point clouds within the plot (Figure 3-6). The individual trees were extracted from the sampled plots (Figure 4-4). From the 26 plots a total of 614 (78.65%) trees were detected out of the 799 trees that were measured from the field using the Leica DISTO. The DBH and Height were measured from the extracted trees.

The trees that were detected were those that were clearly seen with the number tags. Most of the trees that were not detected were obscured by the other trees or as a result of mixed crowns hence making it difficult to be identified from either the 3D view of the data or the TLS photographs that were taken during the scanning process. The height of the identified trees were then manually measured using the RiSCAN pro software. Figure 4-4 shows the (a) a tree detected and coloured in 3D after the multi station adjustment of the scanned plots, (b) and (c) Trees detected and extracted in 3 Dimension and true colour.

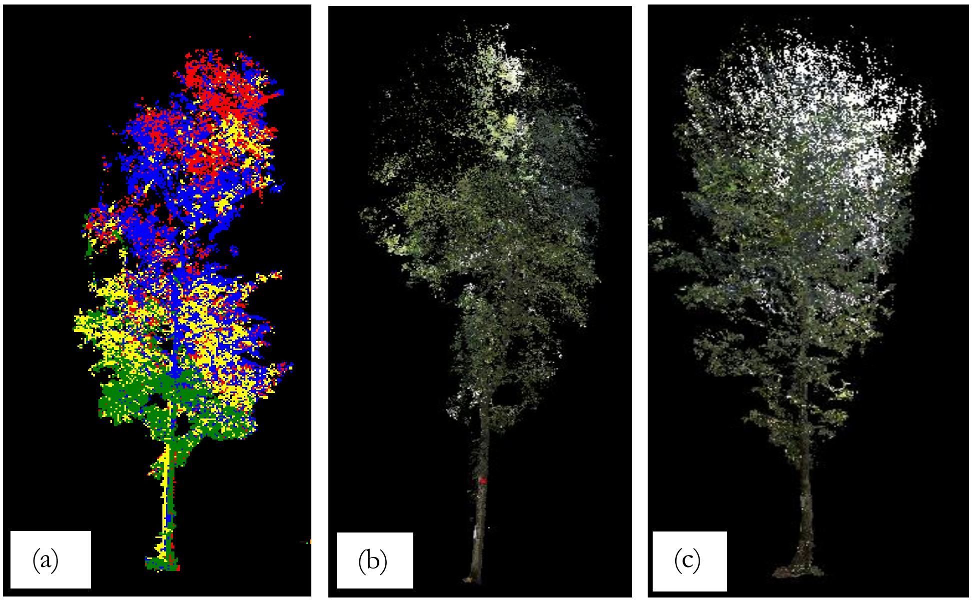


Figure 4-4: A multi station adjusted tree (a) in Plot 13, (b) Tree No. 8 and (c) Tree No. 13 (Plot 11)

The accuracy of scan registration enables the appearing of the tree with all its branches and actual shape in the RiSCAN Pro software. The tree heights were then measured from the bottom to the topmost part while DBH measured at 1.30 cm from the base on the extracted tree stem.

4.2.3. Airborne LiDAR derived tree height

4.2.3.1. Canopy Height Model (CHM)

The CHM was created from the Airborne LiDAR data that was obtained for this study. From the point clouds, a DTM and DSM were created, the DTM was then subtracted from the DSM. Based on the field measured tree height the DSM was generated with point clouds that contained the height ($z - value$) between 0 and 50 meters (Figure 4-6). This means points below Zero (0) and above 50 meters were not considered. Based on the number of points per meter, a CHM of 1 meter spatial resolution was created from the DSM and the DTM. The standard CHM, contained pits and holes due to returns that were from the sub layers or branches below the top of trees. The pits and holes were removed from the standard CHM by using the CHM pit free algorithm (Khosravipour et al., 2014) with the result of pit removal shown in Figure 4-5.

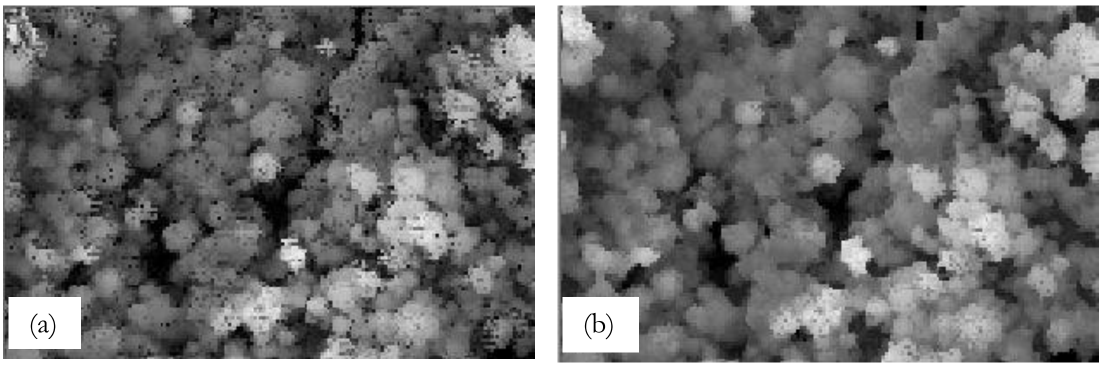


Figure 4-5: Airborne LiDAR CHM with pits (a) and Pit Free CHM (b)

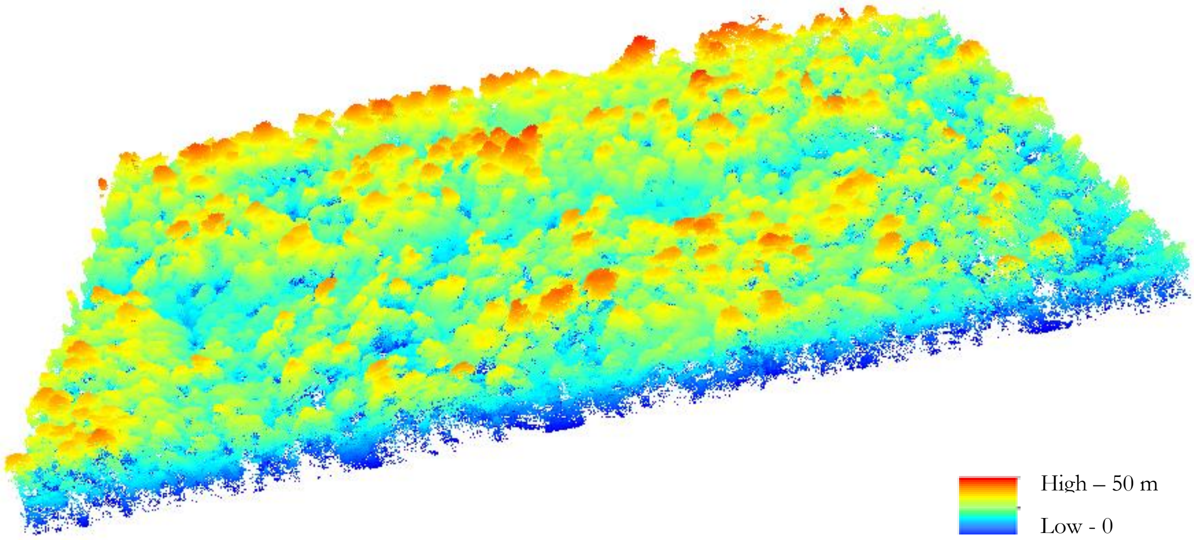


Figure 4-6: 3D view of the CHM (point cloud) in the LasView.

4.2.3.2. Segmentation of the CHM – Estimation of Scale Parameter (ESP)

Before tree crown delineation from the CHM, the value of shape, compactness and scale were established. This helped in estimating the appropriate scale for segmentation in the eCognition software. The appropriate estimation scale for the segmentation was established, with shape 0.1 and Compactness of 0.9 based on the local variance and rate of change (Figure 4-7).

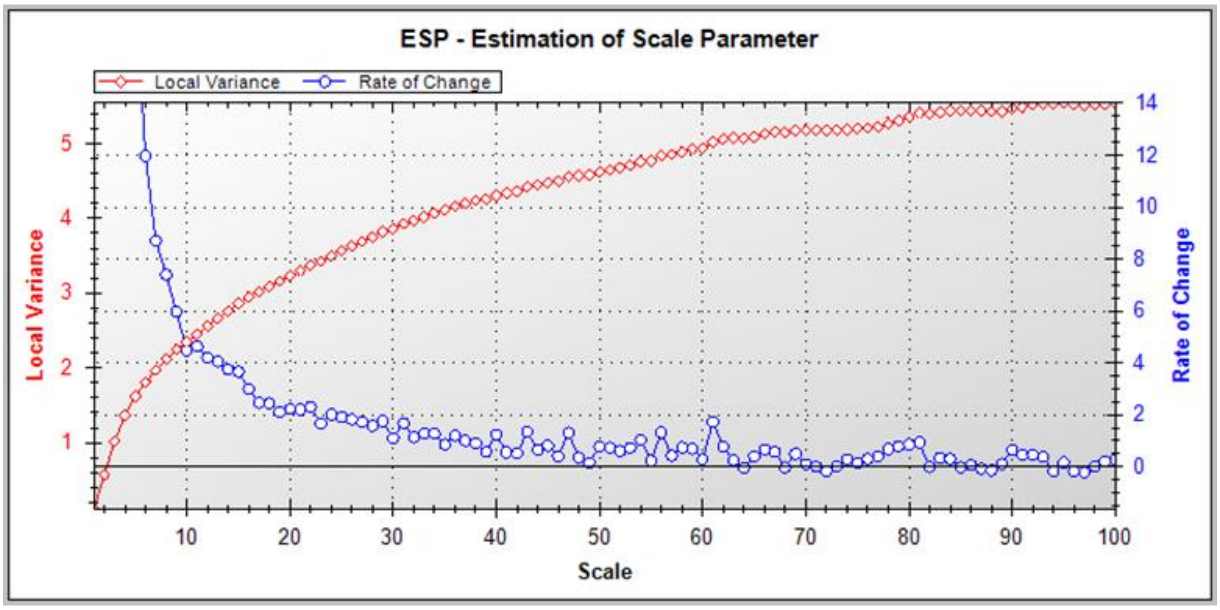


Figure 4-7: ESP for CHM tree delineation and segmentation

Watershed transformation was the main algorithm used since the CHM only shows elevation values with limited or no noise and cloud cover which is a common challenge with satellite imagery. The purpose was to confirm the tree location within the respective tree crowns shown in the CHM. In addition to the Watershed transformation, roundness, compactness and brightness (elevation) parameters were set up to improve the accuracy of the segmentation as well as the identification and matching of the trees.

4.2.3.3. Tree crown delineation on the CHM

The segmented CHM from eCognition software was then exported and used in ArcGIS software to obtain the position of trees as shown in Figure 4-8. The plots were delineated, and then integrated with tree positions identified from the field and TLS measurements.

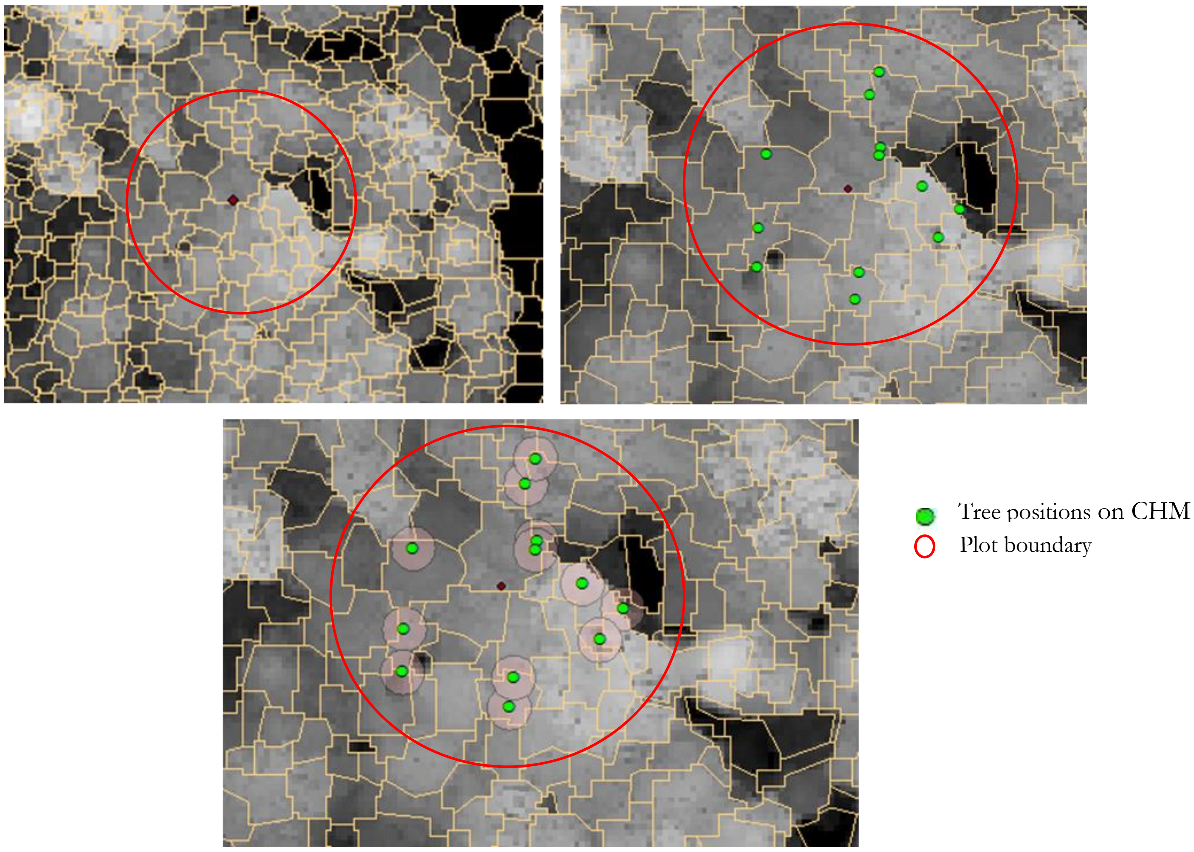


Figure 4-8: CHM tree crown delineation with multi resolution segmentation

The tree tops were then identified using maximal elevation (Bott, 2014) after segmentation of the CHM, the position of the trees were defined (Figure 4-8) by using the GPS coordinates from the field. The centre of the plot coordinates were collected using the Magellan Mobile Mapper 6 with a stated accuracy of 1-2 meters (Hunt & Dinterman, 2014). The individual tree location was further confirmed using the number tag and location on the plot based on the TLS scan positions that contained the location of the tree in scanner own coordinate system. The tree height obtained from CHM was considered to be more accurate than the tree height from the field and measured from the TLS data.

4.2.3.4. Segmentation accuracy and validation

Segmentation accuracy was calculated with the D value of 0.23 (77% accurate), the D value ranges between 0 and 1, where 0 represents perfect match of the manually delineated crowns compared with the segmented crowns from the eCognition software. The 77% accuracy was acceptable since the main aim of the segmentation was to delineate the main crowns for the purposes of tree identification and matching on the CHM and the field measurements so that maximal elevation value would be obtained to measure the tree height.

Therefore a total of 345 trees were matched from CHM with field and TLS measurements and the overall height summarised on table 4-2 and Figure 4-9.

Table 4-2: Summary statistics for the height for the detected trees

	Field measured height [m]				TLS measured height [m]				Airborne LiDAR measured height [m]				
Plot	Mean	Std. Dev.	Min.	Max.	Mean	Std. Dev.	Min.	Max.	Mean	Std. Dev.	Min.	Max.	Count
1	15.47	4.57	8	22	13.27	3.27	7.61	17.28	14.42	3.24	8.43	18.92	12
2	15.72	3.86	8	22	17.14	3.47	11.87	23.32	17.90	3.42	12.49	23.51	12
3	17.90	6.77	10	38	17.67	5.31	7.35	28.71	20.53	4.51	11.93	30.89	20
4	15.15	3.39	9	21	19.43	4.92	8.93	28.51	22.04	3.68	15.25	28.23	13
5	19.94	7.50	8	32	18.88	4.95	9.01	25.35	21.77	4.12	16.03	28.87	18
6	15.38	5.49	6	26	18.44	4.24	10.41	25.31	19.32	4.17	11.88	25.82	16
7	14.36	3.67	9	20	15.07	3.32	10.71	22.38	17.34	3.55	11.49	22.24	11
8	7.75	2.70	5	15	9.29	1.85	6.17	12.07	11.79	2.71	7.47	16.48	12
9	13.38	3.88	7	20	17.01	4.93	9.32	26.01	17.72	4.64	10.91	27.23	13
10	11.58	3.06	7	18	13.67	3.47	8.22	21.00	13.82	3.03	9.05	19.56	12
11	14.33	4.12	10	23	18.28	3.86	10.38	25.62	18.87	3.70	10.96	25.83	12
12	13.82	4.07	8	22	16.41	3.93	10.81	21.52	17.24	3.50	11.78	21.75	17
13	12.31	3.01	6	18	14.83	3.90	9.47	21.64	15.40	4.13	10.40	21.71	13
14	15.54	4.61	11	25	21.48	5.73	15.56	37.34	22.98	5.17	17.16	37.88	13
15	15.00	4.73	10	24	20.88	5.24	14.00	32.54	25.82	3.69	20.62	33.01	16
16	16.93	4.67	7	25	21.83	7.42	9.66	33.63	22.38	7.12	10.69	33.73	15
17	16.00	5.40	8	22	16.91	2.71	13.15	20.16	18.10	3.19	13.08	21.75	8
18	14.57	3.13	6	18	17.84	3.83	10.00	23.00	19.63	3.01	15.32	25.32	14
19	21.33	3.63	16	27	23.32	5.31	15.50	31.00	23.86	4.77	17.03	30.70	12
20	18.57	5.94	10	30	20.34	5.76	11.00	34.00	21.98	5.75	11.96	34.49	14
21	15.92	2.84	13	22	18.92	4.60	13.00	28.00	20.22	4.49	13.37	28.84	12
22	21.54	6.40	14	32	23.20	4.56	16.30	29.70	25.82	5.51	18.65	36.86	13
23	19.15	5.86	6	28	24.93	6.94	11.10	37.57	25.60	6.67	11.52	35.31	13
24	17.45	3.78	10	24	20.03	3.31	13.90	25.30	21.79	4.37	15.67	31.32	11
25	14.82	4.85	8	26	22.17	7.18	12.00	38.00	23.29	6.96	13.31	38.06	11
26	13.82	4.26	7	21	18.05	5.07	11.00	25.90	21.10	5.63	15.19	33.73	11

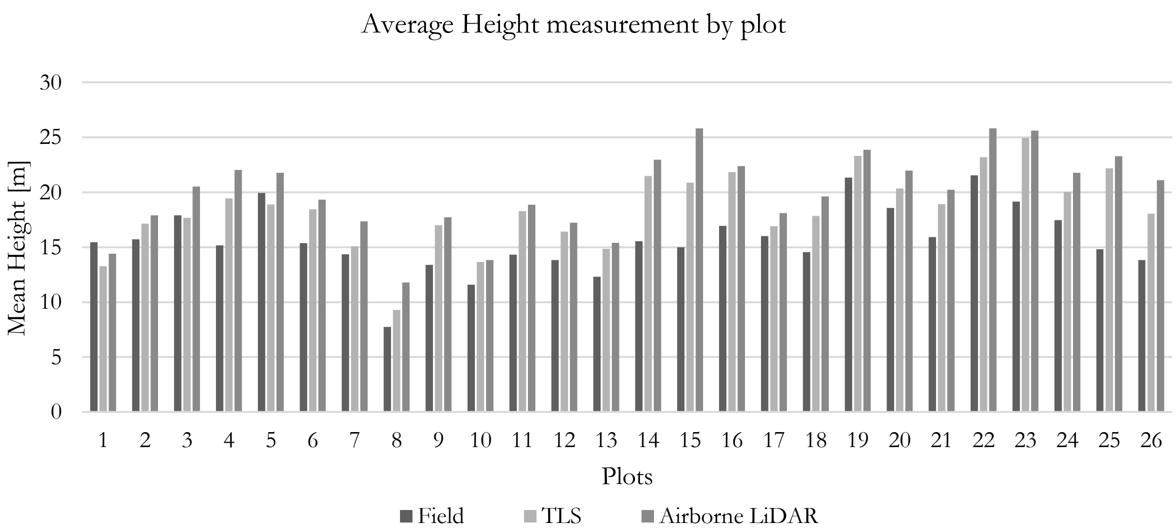


Figure 4-9: Mean tree height per plot for different instruments.

4.3. Accuracy assessment of the tree height measurement

Tree height was measured using 3 different methods mainly manual height measurement from the field using Leica DISTO 510, measurement from 3 Dimensional TLS scans and Airborne LiDAR derived CHM. The tree height measurement were validated using the linear regression model, Pearson's correlation coefficient and one way ANOVA, with Airborne LiDAR- derived tree height taken as the standard for validation based on its stated accuracy.

In this evaluation, a total of 312 individual trees were measured from field and detected on TLS 3D point clouds. The same trees were also matched and measured on the Airborne LiDAR CHM. The Airborne LiDAR measurement was used as the basis to assess the accuracy.

4.3.1. Accuracy of field measured tree height

The field measured height were matched with the Airborne LiDAR height. A summary descriptive statistic shown in Table 4-3. The relationship between field and Airborne LiDAR measurement were then established

Table 4-3: Summary statistics of matched field and Airborne LiDAR trees.

Statistics	Airborne LiDAR [m]	Field Height [m]
Mean	19.59	15.59
Standard Deviation	5.23	5.02
Minimum	7.47	5
Maximum	35.31	32
Count	312	312

Best of fit of the field height was evaluated in R statistics with the summary of regression equation. The field measured height was considered as a dependent variable while the Airborne LiDAR derived height as an independent variable for the linear regression represented in the Figure 4-10. The R^2 of 0.61 was established with RMSE of 4.20 (21.45%) with correlation coefficient of 0.78.

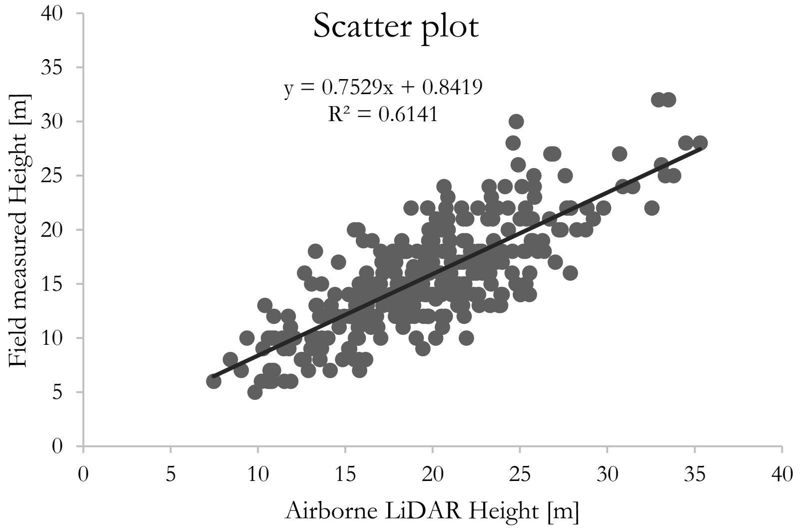


Figure 4-10: Scatterplot for field height and Airborne LiDAR measured height

Summary of the relationship and validation of field measured height using Airborne LiDAR is shown in Table 4-4 and the scatter plot for the relationship is shown in Figure 4-10.

Table 4-4: Summary statistics for the field height and Airborne LiDAR height

Summary of fit	
Correlation Coefficient	0.7837
R Square	0.6141
Adjusted R Square	0.6129
Standard Error [m]	3.1247
Root Mean Square Error (RMSE) [m]	4.2010
Observations	312

4.3.2. Accuracy of TLS height

The TLS scan plots were downloaded from the scanner and registered to one common principal scan to form the 3 Dimension view of the plots. 26 plots that were scanned from the field were all registered with minimal possible error of less than 0.02 m after multiple scan adjustment in the RiSCAN Pro software was done (Table 3-3).

Then the individual trees were detected, extracted and the heights measured. From the 26 plots a total of 614 (78.65%) trees were detected out of the 799 trees that were measured from the field using the Leica DISTO 510. The number of trees extracted from TLS were then matched with 345 trees from Airborne LiDAR and then 312 of these trees were then considered for analysis. The DBH and Height were measured from the extracted trees. Validation of TLS height was carried out using the Airborne LiDAR CHM derived tree height, Table 4-5 indicates the summary statistics of the measurements and Figure 4-11 shows the scatter plot.

Table 4-5: Summary statistics for matched trees from TLS and Airborne LiDAR

Statistics	Airborne LiDAR [m]	TLS Height [m]
Mean	19.59	18.26
Standard Deviation	5.23	5.46
Minimum	7.47	6.17
Maximum	35.31	37.57
Observations	312	312

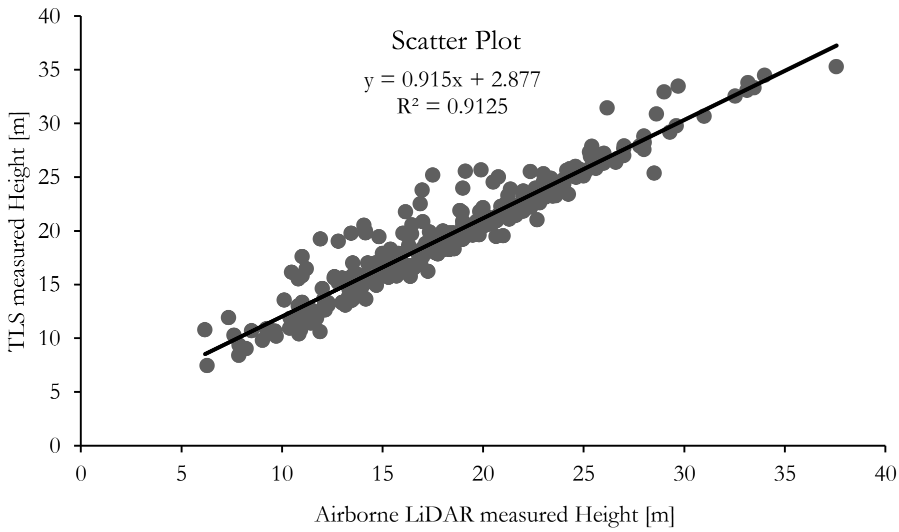


Figure 4-11: Scatter plot for the relationship between TLS and Airborne LiDAR height

The best of fit for the TLS measured height with Airborne LiDAR indicate that the $R^2 = 0.91$ and Pearson's correlation coefficient of 0.96 with RMSE of 1.33 (6.76%) as indicated in Table 4-6.

Table 4-6: Summary statistics for TLS height and Airborne LIDAR height

Summary of fit	
Correlation Coefficient	0.9552
R Square	0.9125
Adjusted R Square	0.9122
Standard Error [m]	1.6172
RMSE [m]	1.3248
Observations	312

4.3.1. Relationship between field and TLS height

The field measured height and TLS were compared to assess their relationship. Field height showed a RMSE of 4.20 m when validated using Airborne LiDAR while the TLS had RMSE of 1.33 m when validated using the same Airborne LiDAR data. In this case the TLS height proved to be more accurate than the field measured height. The two height measurements (field and TLS) were then assessed to establish how they were related by using TLS as independent (x) and field as dependent (y) as shown in Figure 4-12.

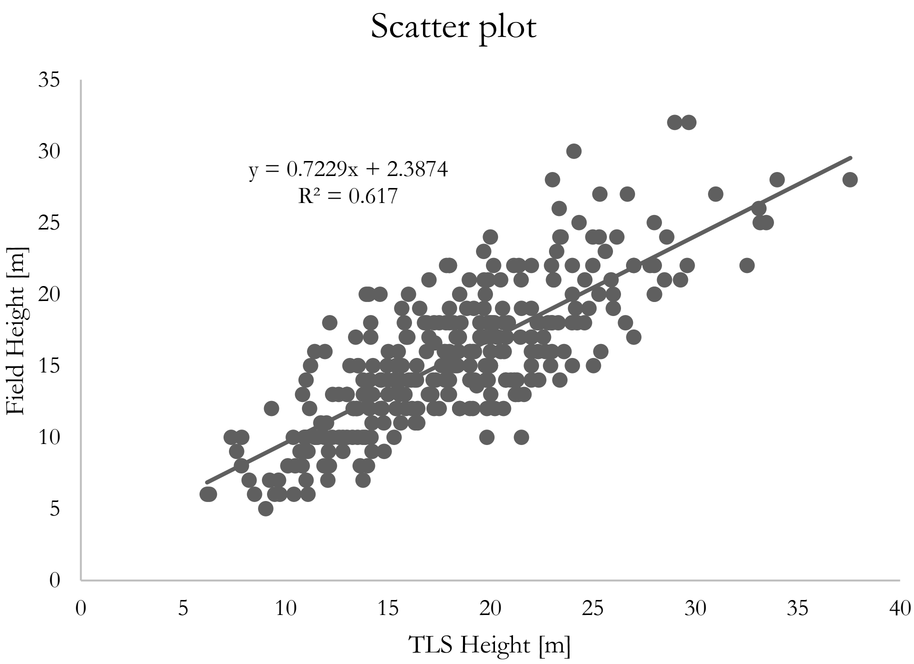


Figure 4-12: Scatterplot for the relationship between field height and TLS height

The result obtained revealed that the relation between the field height and TLS height was explained by the correlation coefficient of 0.79 and R^2 of 0.62 with RMSE of 3.07 m as shown in the summary (Table 4-7). Despite having high correlation, the RMSE was closer to when field measured height was compared with Airborne LiDAR.

Table 4-7: Relationship between field and TLS measured height

Summary of fit	
Correlation Coefficient	0.7855
R Square	0.6169
Adjusted R Square	0.6158
Standard Error [m]	3.1130
RMSE [m]	3.0703
Observations	312

4.4. Height differences between Field, TLS and Airborne.

The difference between the tree height measurements from field, TLS and Airborne LiDAR were assessed in a statistical analysis. A single factor ANOVA was done to assess the variance of the means between the 3 measurements of the tree height. The ANOVA was followed by a protected t-Test, since there was high correlation between the individual measurements.

Table 4-8: A single factor ANOVA for the field, TLS and Airborne LiDAR height

Groups	*Count*	*Sum*	*Average*	*Variance*
Field Height [m]	312	4864.2	15.59038462	25.22112911
TLS Height [m]	312	5698.333	18.26388782	29.77774389
Airborne LiDAR [m]	312	6111.64	19.58858974	27.32325653

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2588.362277	2	1294.181139	47.16281562	0	3.005371773
Within Groups	25602.18228	933	27.44070984			
Total	28190.54456	935				
$F>F_{Critical}$: *Decision:* There is variation in the height measurements.						

The result of ANOVA (Table 4-8) shows that, there was significant difference between the mean of tree heights measured from field, TLS and Airborne LiDAR. Despite the significant different, there was high correlation between the height measurements, therefore, as a follow up to the ANOVA, a protected t-test was done to further understand the variation between the height measurements.

Table 4-9: t-Test for field height and Airborne LiDAR height.

	Field Height [m]	Airborne LiDAR [m]
Mean	15.5904	19.5886
Variance	25.2211	27.3233
Observations	312	312
Pearson Correlation	0.7837	
df	311	
t Stat	-20.9162	
P(T<=t) one-tail	1.44012E-61	
t Critical one-tail	1.6498	
P(T<=t) two-tail	2.88024E-61	
t Critical two-tail	1.9676	

The t-Test result in Table 4-9 revealed that, there was a significant difference between the height measurement from field and the Airborne LiDAR.

Table 4-10: t-Test for TLS height and Airborne LiDAR height

	TLS Height [m]	Airborne LiDAR [m]
Mean	18.2639	19.5886
Variance	29.7777	27.3233
Observations	312	312
Pearson Correlation	0.9552	
df	311	
t Stat	-14.4913	
P(T<=t) one-tail	5.07643E-37	
t Critical one-tail	1.6498	
P(T<=t) two-tail	1.01529E-36	
t Critical two-tail	1.9676	

The t-Test result between TLS and Airborne LiDAR height measurements show that, there was a significant variation in the height measurements, Table 4-10 shows a summary of the t-Test result.

Table 4-11: t-Test for field height and TLS height

	Field Height [m]	TLS Height [m]
Mean	15.5904	18.2639
Variance	25.2211	29.7777
Observations	312	312
Pearson Correlation	0.78549	
Hypothesized Mean Difference	0	
df	311	
t Stat	-13.6629	
P(T<=t) one-tail	6.51879E-34	
t Critical one-tail	1.64977	
P(T<=t) two-tail	1.30376E-33	
t Critical two-tail	1.96762	

Table 4-11 shows the t-Test result between field and TLS height measurements, there was a significant variation in the height measurements from field and TLS as shown by the test results. Although, the correlation coefficient between the height measurements were high, there was significant variation or differences observed when a protected t-Test was done for the height measurements.

Considering the significant differences, regression analysis was done to quantify the errors associated with the tree height measurement from the three (3) different methods that were used in this study. Table 4-12 to 4-14 show the regression results between the height measurements.

Table 4-12: Summary regression statistics: Airborne LiDAR and Field

Regression Statistics	
Multiple R	0.783660591
R Square	0.614123922
Adjusted R Square	0.612879161
Standard Error	3.12467993
Observations	312

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	4817.047507	4817.047507	493.366723	4.57434E-66
Residual	310	3026.723647	9.763624667		
Total	311	7843.771154			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	0.841906399	0.687152023	1.225211265	0.221425715
Airborne LiDAR [m]	0,.75291169	0.033896832	22.21185996	4.57434E-66

RMSE =4.20 (21.45%) Standard Error= 3.13 m, $R^2 = 0.61$, Alpha = 0.05, (P-value< alpha)
Decision; There was significant difference

Table 4-13: Summary regression statistics: Airborne LiDAR and TLS

Regression Statistics	
Multiple R	0.955223528
R Square	0.912451988
Adjusted R Square	0.912169575
Standard Error	1.617217333
Observations	312

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	8450.10686	8450.10686	3230.914211	5.2947E-166
Residual	310	810.7714893	2.615391901		
Total	311	9260.878349			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	-1.269962108	0.355644158	-3.57087859	0.000412251
Airborne LiDAR [m]	0.997205525	0.017543731	56.84113133	5.2947E-166

RMSE =1.33 (6.76%), Standard error =1.62 m, $R^2 = 0.91$, Alpha = 0.05, (P-value< alpha),
Decision; There was significant difference

Table 4-14: Summary regression statistics for TLS and Field relationship

Regression Statistics	
Multiple R	0.785490839
R Square	0.616995859
Adjusted R Square	0.615760361
Standard Error	3.113030282
Observations	312

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	4839.574318	4839.574318	499.3907258	1.43366E-66
Residual	310	3004.196836	9.690957536		
Total	311	7843.771154			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	2.387442386	0.616539922	3.872324077	0.00013151
TLS Height [m]	0.72289878	0.032348732	22.34705184	1.43366E-66

RMSE =3.07 (16.81%), Standard error =3.11 m $R^2 = 0.62$, Alpha = 0.05, (P-value< alpha), *Decision;* There was significant difference

4.5. Above Ground Biomass estimation

The AGB for the individual 312 trees identified was calculated using the Allometric equation with the tree inventory parameters from field mainly DBH and height, TLS derived tree height and the Airborne LiDAR derive tree height from the CHM. The field tree height and the TLS derived height were validated using the Airborne LiDAR derived height. The observed trees from the field were matched with Airborne LiDAR CHM using the TLS number tags and positioning. The global wood density (WD) of 0.57 (UN-REDD 2013) for Asia and South Eastern Asia was used as an input to the allometric equation.

Table 4-15: Estimated AGB for the selected trees

Statistics	Field Measurement	TLS	Airborne LiDAR
Mean Biomass (Mg)	0.47	0.55	0.58
Standard Deviation	0.62	0.74	0.76
Minimum	0.017	0.022	0.026
Maximum	5.869	7.127	7.229
Total Biomass (Mg)	146.33	170.86	179.85
Observations (Trees)	312	312	312

The amount of AGB (Table 4-15) from field height measurement, TLS and Airborne LiDAR were significantly different based on the statistical test done which indicated that there was significant difference between the AGB form field and Airborne LiDAR (18.6%), TLS and Airborne LiDAR (4.99%) and TLS compared with field (14.36%) difference. The result implies that field measured height only estimated 81.29% of AGB when Airborne LiDAR is used as the standard, meanwhile TLS estimates 95.02% of AGB that was obtained by the Airborne LiDAR.

The results further revealed that there was significant difference between the amount of AGB from the heights measured using the 3 (three) methods as indicated in Appendix 1 and 2, which shows the summary relationship between the AGB and consequently carbon stocks for the different measurements.

4.6. Carbon stock estimation

The amount of tree carbon was obtained from the AGB as carbon is composed of 0.47 of the above ground biomass (AGB) for the trees (IPCC, 2007). Consequently based on the amount of AGB, there was also significant difference in the carbon stock (Table 4-16) basing on the different height measurements since carbon is a portion of the calculated AGB.

Table 4-16: Carbon stick for the selected trees

Statistics	Field Measurement	TLS	Airborne LiDAR
Mean (Mg)	0.2204	0.2574	0.2709
Standard Deviation	0.2893	0.3483	0.3569
Minimum	0.0082	0.0104	0.0123
Maximum	2.7586	3.3497	3.3980
Total Carbon stock (Mg)	68.7728	80.3054	84.5281

The results showed that for the 312 trees observed, the total carbon stock was 68.77 Mg for field height measurement, 80.31 Mg for TLS measurement and Airborne LiDAR was 84.53 Mg which showed significant difference between the measurements. Appendix 3 shows the statistical tests to provide evidence for the significant differences.

4.7. Effects of error propagation and sensitivity analysis

The errors in the tree height measurement range from the errors associated with the instruments, the actual measurements and the conditions in the forest especially the canopy/crown structure, slope/landscape that hamper accurate measurement of the tree height. These error once introduced, propagate in to the estimation of the AGB. In this study, the errors in tree height measurement were quantified and used for varying the actual height measurements to assess how they affect the overall estimation of AGB and consequently carbon stocks.

The errors then propagate in to the estimation of the AGB. The amount of tree biomass was found to be sensitive to the changes in the height. Tree biomass for 25 selected trees were plotted for the different methods (field measurement) with an adjusted height by ±4 m due to the RMSE of 4.20 m (Figure 4-14), TLS height measurement was adjusted by ±1.5 m based on the RMSE of 1.33 m (Figure 4-15). The sensitivity of the actual height measurements from field, TLS and Airborne LiDAR were also assessed to see how sensitive AGB was to the different the measurements (Figure 4-16). In this case, biomass was underestimated or over estimated by the field measurement that was associated with standard errors of ±3.12 m as well as ±1.62 m for TLS to measure tree height.

The difference in the height measurements from field, TLS and Airborne LiDAR showed a great variation in the amount of AGB measured from the trees. The differences were regarded as a result of the operationalization of the methods, especially, the height data from TLS and field measurement were collected from ground surface level and posed difficulty in detecting the actual tree top that defines the tree height meanwhile the Airborne LiDAR allows the capture of the information about the top of the trees from the air above these trees. This method was considered as very accurate since it sees and detects the actual tree height from the air above the trees. The TLS and field measurement were affected with critical challenge of occlusion which significantly influences the accuracy of measurements, this does not affect the Airborne LiDAR. Figure 4-13 shows the operationalization of the various systems used in the study.

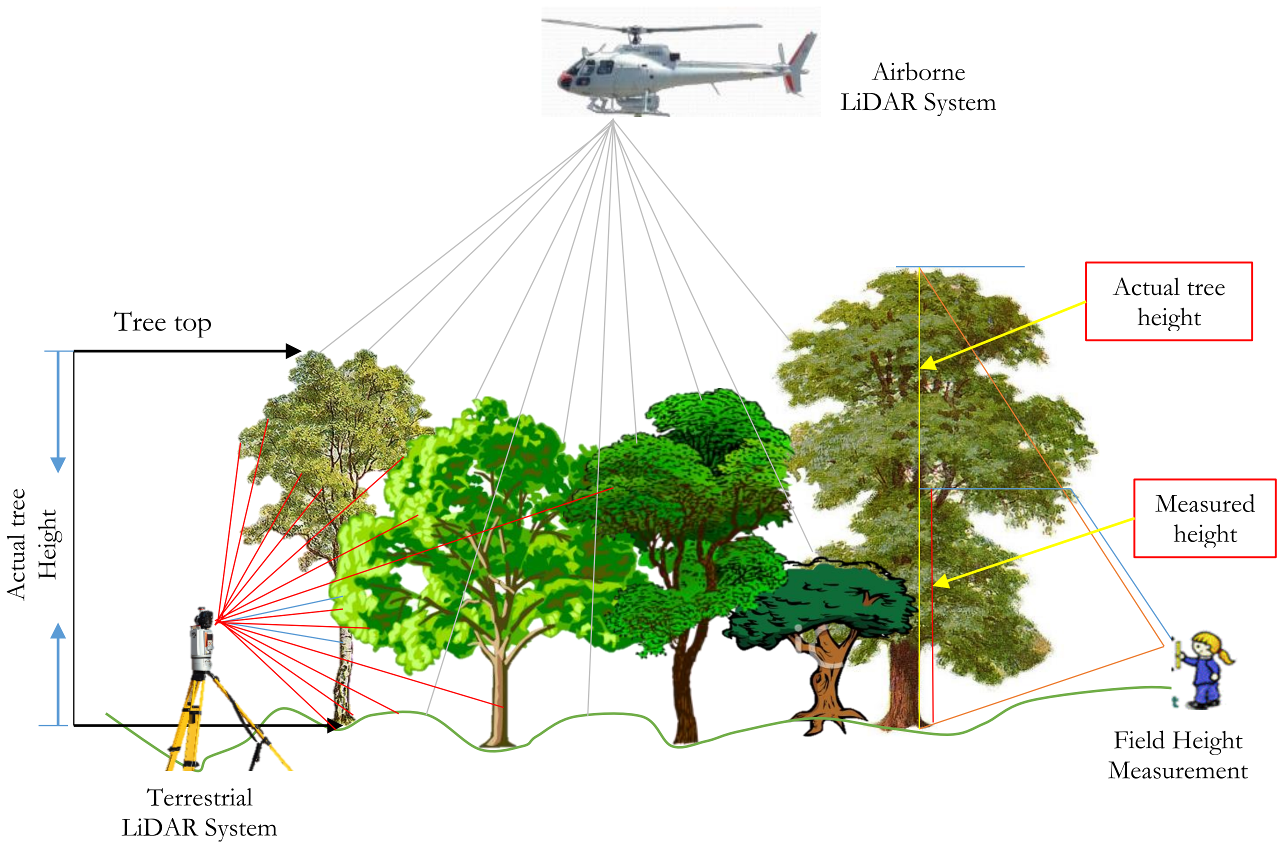


Figure 4-13: Operationalization of the height measurement methods.

The quantified errors in tree height measurements were used to assess the sensitivity of AGB to the changes. Field measured height was varied by ±4 m based the quantified standard error and the RMSE from the validation. A scatter plot was done for individual trees to visualize the sensitivity of the AGB to height errors The scatter plot, for the selected number of individual trees were plotted with the respective amount of AGB with height varied eight (8) times by adding values ranging from -4 to +4 to the actual tree height measurement.

Figure 4-14 shows the scatter plot with variation in the amount of AGB as represented with actual field biomass from the actual field measurement as Biomass_Field (Mg), with the varied height ranging from field -4 to field +4 as shown in the legend.

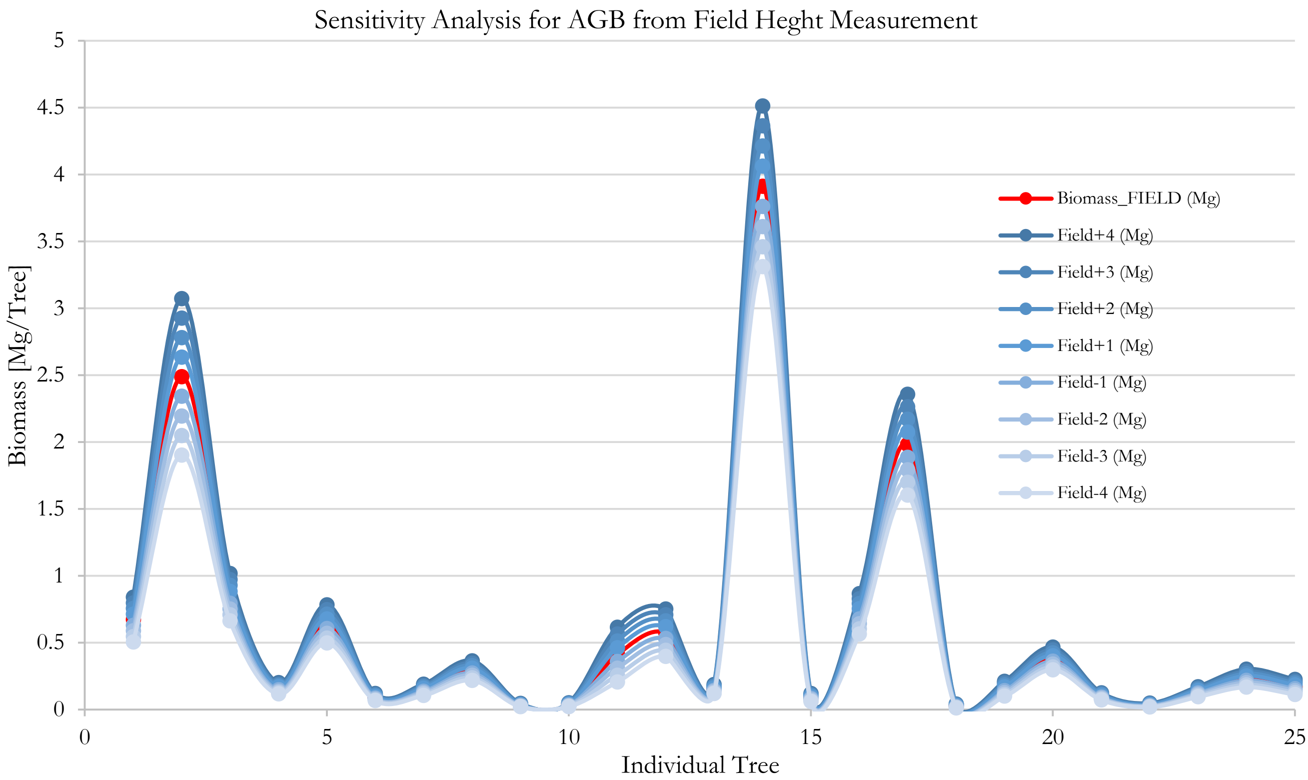


Figure 4-14: Sensitivity analysis of AGB to tree height varied based on the accuracy of field height.

The validation of the TLS measured height resulted in to an acceptable accuracy with R^2 of 0.91 and correlation coefficient of 0.96 with the Airborne LiDAR measurement. The RMSE was 1.33 m. based on the RMSE, the TLS measured height was adjusted two (2) times by ±1.5 m, the adjusted value shows the changes in AGB as shown in Figure 4-15.

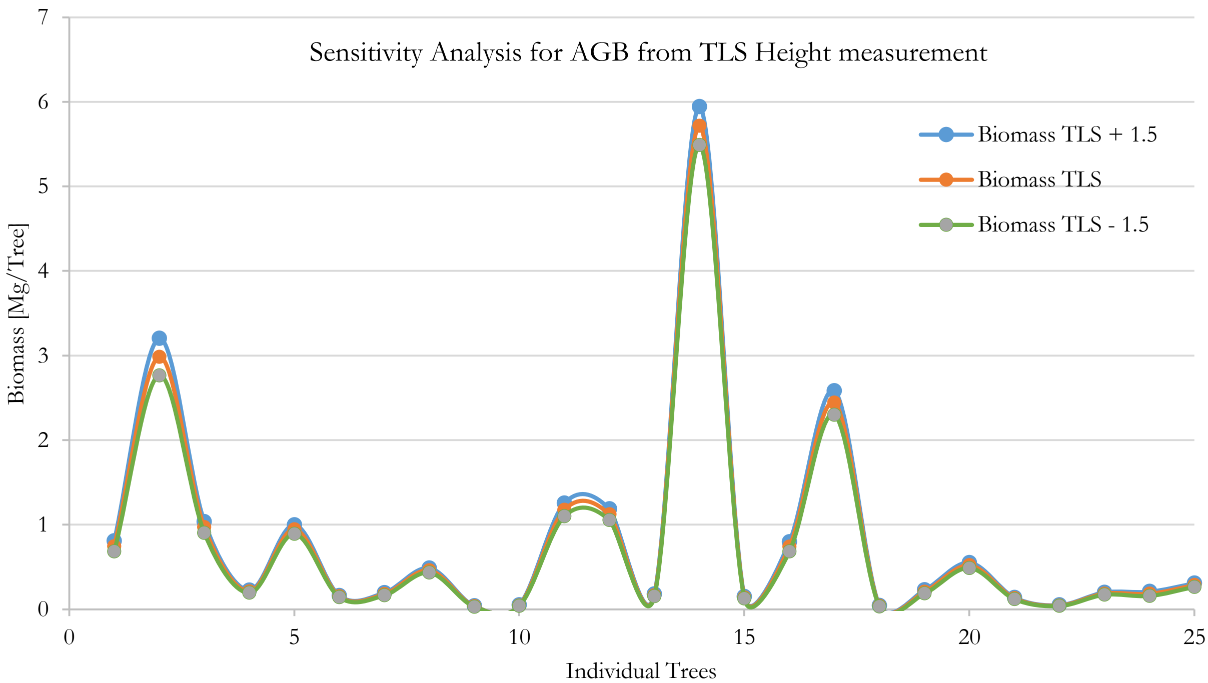


Figure 4-15: Sensitivity analysis of AGB to tree height varied based on the accuracy of TLS height.

The changes in the measured height based on the error showed that, there was a change in the amount of AGB. This consequently affects the amount of carbon stock for the individual trees.

The errors associated with the height measurement were then included in the final biomass calculation and therefore either underestimate or overestimate tree biomass. In this study, it was found out that the tree height was in most measurements under estimated approximately by ±3.12 m from the field measurements and by ±1.5 m from the TLS. Based on the error, the tree height was varied by ±4 to understand the amount of AGB changes in response to the adjusted tree height for field measurement and ±1.5 m for the TLS measured height. This therefore indicated that the AGB was very sensitive to changes in the tree height.

The field, TLS and Airborne LiDAR measured heights were further assessed together using scatter plot to see if the differences would be significant on the AGB (Figure 4-16)

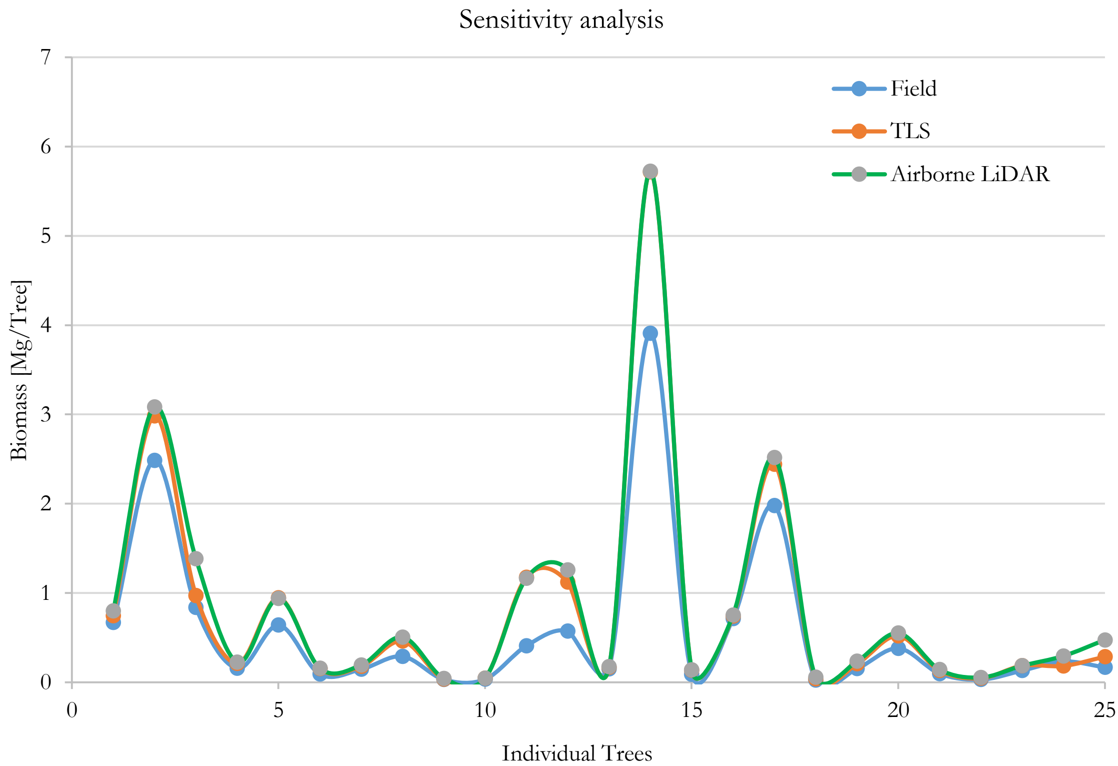


Figure 4-16: Sensitivity analysis of AGB to tree height based on the actual height measurements.

The sensitivity line indicated that if the height was changed, it affected the amount of AGB. Therefore, errors from tree height measurement potentially affect the amount of AGB. Figure 4-16 further shows that the AGB measured from Airborne LiDAR were significantly higher followed by TLS and then the field measured AGB was the smallest. With high tree height values, the AGB amount for TLS and Airborne LiDAR were closely related to each other as opposed to the field measurement. In overall sensitivity analysis, the result indicated that the AGB and Carbon stocks were underestimated by the field and TLS height measurement.

5. DISCUSSION

5.1. Field Data Collection

Diameter at Breast Height (DBH) and height of 345 trees (Appendix 6) were measured from 26 plots that were sampled during the field work. The DBH data showed non-normal distribution with DBH positively skewed. Figure 5-1, shows the histograms showing the positive skewness of the distribution of the DBH Measurements for field and TLS Scans.

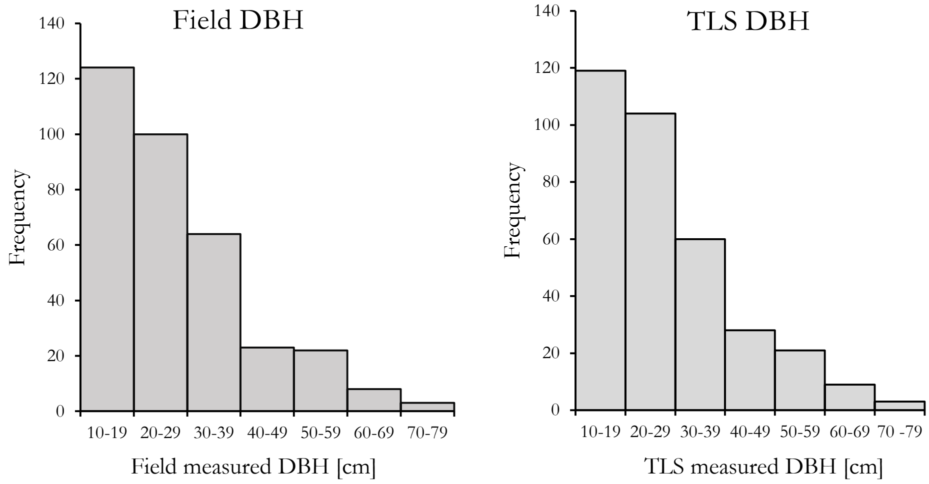


Figure 5-1: Histogram showing the positively skewed DBH

The DBH measurement indicates positive skewness since tree with only DBH greater or equal to 10 cm were considered for the measurement. The extreme measurements far from the tail were considered as outliers. Out of the 345 trees that were matched on all the measurements, one (1) tree was considered as an outlier based on the deviation from the tail of the distribution, when critically investigated, during the field work, this particular tree was one of the poisonous species identified from the field. Therefore, there was caution in its measurement hence deviating from the mean of other measurements, however in the TLS Scan the actual DBH of the particular tree was measured with wide difference from the field measurement. Figure (5-2) indicates the tree with error in field measurement due to poisonous status.

Figure 5-2: Tree No. 1 (Plot 2) a poisonous tree that was difficult to measure the DBH in the field.

DBH was also measured using the TLS, this was carried out through horizontal slicing at 130 cm height of the tree, and the measurement produced a highly accurate result with R^2 of 0.97 with RMSE of 0.26 when validated using field measured DBH. The result is comparable with (Bienert et al., 2006b; Maas et al., 2008; Srinivasan et al., 2015a) who obtained R^2 that ranged from 0.91 to 0.97 when TLS measured DBH was validated against field measurement of DBH.

5.2. Tree Height Measurement

5.2.1. Tree height measurement using Leica DISTO 510

During the field work, tree height was measured. The field instrument used was the Leica DISTO 510 laser distance. The instrument uses a laser based technology, once the laser hits an object, especially a branch of tree or leaf but not the top of the tree, it records the information as the top most point for the tree height. This therefore introduces errors in to the true height measurement, mainly the underestimation of the tree height. Distance from measured (branch/crown) and true horizontal distance to the crown can lead to unbiased errors (Hunter et al., 2013). This was observed in situations where the tree trunks were not well projected, displacement of the crown tops from the trunk location. Figure 3-8 indicates a tree that has been bend and with varying height measurements of 5 m and 8.39 m from field and TLS respectively. However the actual height that is relevant for AGB estimation of the tree may be different from all the recorded height measurements. The same tree could not be visible to the Airborne LiDAR given that its crown is below the crowns of the other trees.

Ayer Hitam is a secondary tropical rain forest, therefore, occlusion of trees was one of the main challenges that made it increasingly difficult to view the exact height or top most part of the tree to establish and measure the actual tree height. Hence in most situations tree height was either over estimated when another top crown of another tree was captured for a particular tree or under estimated when the laser hits on the branches that are not the top most part of the tree. Using the Leica DISTO 510 requires unblocked path from the laser ranger to the top of the tree (Larjavaara & Muller-Landau, 2013) and this was observed and experienced during the field work in Ayer Hitam.

The handheld laser ranger returns only one distance from the multiple objects that it hits. This presented a challenge during the field work where the trees had varying heights that could potentially block the top most part of the tree. Figure 4-13 explain why the ground/terrestrial based field measurement using the Leica DISTO 510 laser ranger and the RIEGL VZ-400 TLS were having the problem capturing the real top part of the tree. The method required visibility of the base of the trees, this was enhanced by the clearing of the massive undergrowth for the TLS Plots during the field work. Various studies that have compared the tree height measurements using field equipment have considered tree height in perfect visibility of the top with limited focus on the leaning as well as limited visibility.

The study was designed to carry out field measurements using TruPulse laser range finder alongside with Leica DISTO 510, however due to the complexity and occlusion in the forest (Figure 4-3b) where the tree crowns cannot be visible, the use of TruPulse could not be effected within the sampled plots.

The height measurement using the Leica DISTO 510 resulted in to RMSE 4.20 (21.44%) meaning 78.56% accuracy when validated using the Airborne LiDAR. This was attributed to difficulties in observing the exact tree top due to the slope which has an influence on the height measurement as well as occlusion by the crown structure. Slope introduces displacement of the crown from the tree stand and this significantly has an influence on the overall height measurement as indicated by (Khosravipour et al., 2015). In this case the crown and other parts will block the person who does the measurement from aiming at or seeing the top of the tree (Figure 5-3).

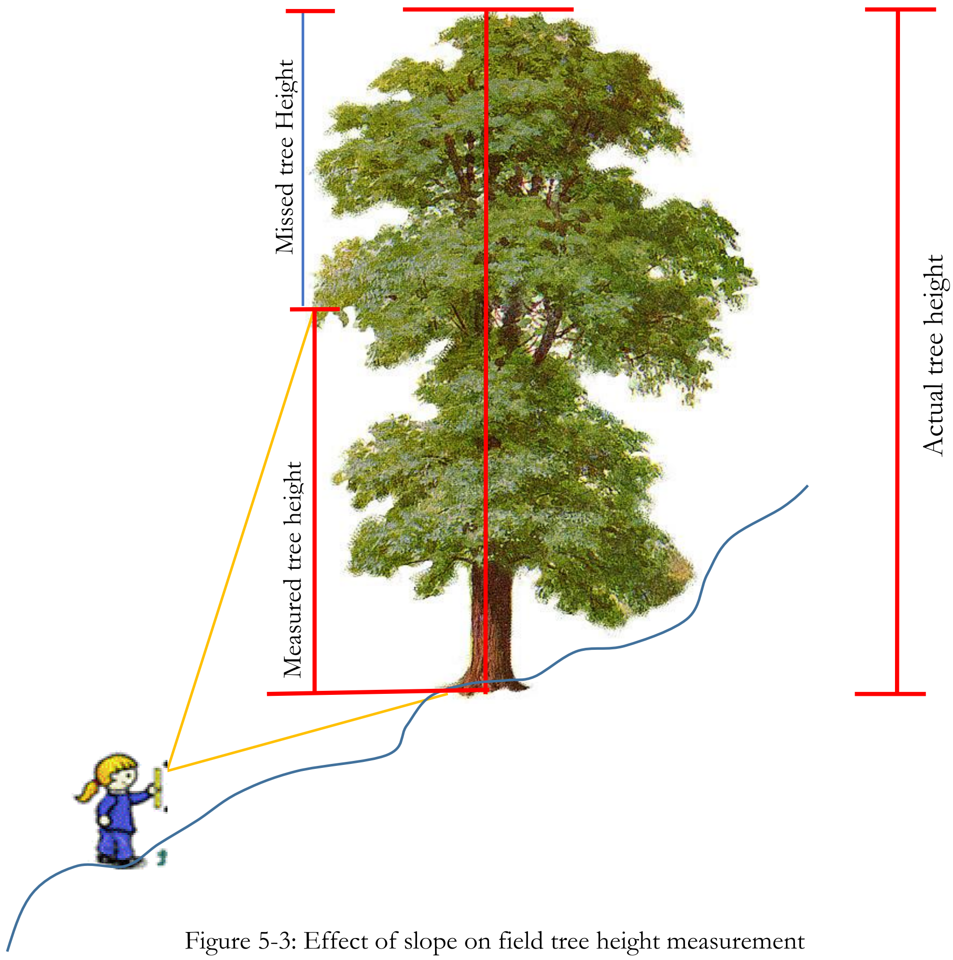


Figure 5-3: Effect of slope on field tree height measurement

The field height was validated using the Airborne LiDAR CHM derived height, with an R^2 of 0.61, correlation coefficient of 0.78 and RMSE of 4.20. The results is comparable with the results of Ginzler & Hobi, (2015) who obtained a correlation ranging from 0.61 - 0.83 depending on varying elevation, after validating field height measured from Ultra Vertex Hypsometer using CHM from image matching of stereo images of which Airborne LiDAR CHM offers better accuracy. The result could be associated with the difficulties of viewing the top of the tree since measurements are carried out in the field using the handheld Leica DISTO 510 with a reported threshold accuracy of ±50 cm compared to the Airborne LiDAR which views the top of the tree with a threshold accuracy of ±10 cm.

The accuracy of field height measurement during this study falls below the previous studies where mainly other hypsometers like Clinometer were used to carry out field data collection (Brandtberg et al., 2003) with a 1.1 m standard error (R^2 = 0.68). It should be noted that, the studies reported with high height measurement accuracy were carried out in temperate forests as well plantation, where tree height is relatively the same compared to the multi-layer tropical forest like Ayer Hitam with lots of differences. The field measured height results from this study compared to those obtained from Table 2-3 indicated that field measurement had low accuracy as this can be explained by the challenges in measuring tree height in multi-layer secondary tropical rain forest with mixed canopies and occlusion of the top of the tree. This could also be attributed to the fact that the previous studies listed (Table 2-3) used the field measurement as a standard meanwhile this study considers Airborne LiDAR as the standard measurement.

5.2.2. Tree Height measurement using TLS and Validation.

Tree height measurement from TLS was done after processing of the multiple scans of the various plots. The main activities/processes involved were registration of multiple scans, multi station adjustment, detection and extraction of the individual trees. During this study, all the 26 plots scanned from the field were registered and multi station adjustment carried out with desirable accuracy (standard deviation) ranging between 0.02 m for plot 17 to 0.01 m for plot 11, with plot 11 more accurately registered. The MSA results in the study are comparable with Prasad, (2015) where a desirable accuracy below 0.02 m was also reported for 24 plots. Table 3-3 shows the detailed MSA accuracy. The MSA accuracy is influenced by the slope and the position of the reflectors within the plot and scan position set up during the field work.

From the registered plots, the point clouds were displayed with true colour to detect the trees and carry out extraction using the selection tools in RiSCAN Pro. This method involves subjective techniques for identifying trees in a point cloud for a tropical rainforest which is characterised by mixture of tree crowns where it is difficult to differentiate between the respective crowns. The number tags that were placed on the tree stem were used to identify and extract the individual tree after the point clouds were coloured using eight overlapping photographs for every scan position (Figure 5-4) that were captured using the TLS scanner mounted camera. Once a taller crown is assigned to another adjacent tree, this means the height may not be accurately measured since the base and the top most point cloud were not matched to accurately measure the height for the particular tree.

Figure 5-4: Overlapping scan images from the TLS showing tree No. 17 (Plot 8) on two images.

The tree height was manually measured after the extraction of the 614 trees from the registered TLS plots. The manual measurement has been reported to have a good accuracy compared with automatic measurement (Prasad, 2015b) in a study that was carried out in Royal Belum forest in Malaysia where the same specified TLS scanner system was used with a total station system. However, in Prasad, (2015) tree height from TLS was validated using the field measured height where as in this study, Airborne LiDAR height was considered as the standard for validation. It is found that Airborne LiDAR have the most accurate measurements of height since it sees the top of the tree very clearly and the error is estimated of ±10 cm. (Figure 4-13).

In this study, the TLS measured height was validated using the height measurement from Airborne LiDAR. Out of the 614 trees that were extracted from the 26 plots, 345 were matched on the Airborne LiDAR CHM. These matched trees were assessed and 33 were identified as outliers based on their height measurement difference in a distribution curve. The 312 trees were used to assess and validate the accuracy of the TLS derived tree height. The results indicated that the Airborne LiDAR derived height was highly correlated with the TLS height with R^2 of 0.91 with RMSE of 1.33 m.

Despite the effect of occlusion within the plot, TLS has the potential to obtain the structure and the full view of the tree. However, the minor difference between the TLS and Airborne LiDAR measurement are due to the fact that there are limitation to laser pulse reaching the tree top from the ground. This is because the laser pulse would be blocked by the leaves of the various layers in the tropical rainforest of which, the study area was not an exception.

Based on the accuracy and the potentials of the terrestrial laser scanning, it would be noted that the TLS method fills the gap between tree scale field manual measurements and Airborne LiDAR measurements by ensuring accurate assessment for the part below crown (Dassot et al., 2011). The tree height measurements based on TLS showed a comparable accuracy when validated against Airborne LiDAR measurement. However, when TLS height measurement was compared with the field height, the results showed low correlation as compared to (Srinivasan et al., 2015b) with an accuracy of 92% of height with RMSE of 1.51 m was reported. It can be argued that their study was done in a plantation forest with trees that have relatively similar heights while the current study was done in a secondary tropical rainforest with several layers and considerable occlusion. Hence field height measurement was a challenge if the definition of tree height been the distance between 2 horizontal planes defined by the bottom and the topmost part of the tree. In this case most of the tree tops cannot be clearly viewed by both the TLS and the field measurement equipment. This therefore makes the Airborne LiDAR to be the only realistic technology to measure tree height since it observes the top most part of the tree (Figure 4-13).

5.2.3. Airborne LiDAR CHM and Accuracy.

The Airborne LiDAR based canopy height model (CHM) was derived from the Airborne LiDAR acquired with 5-6 points/m^2. The LiDAR data was obtained in xyz format and converted to las format usable in the LasTools. A number of processes were done to generate the CHM from which the tree height was measured. The Airborne LiDAR data has a relative accuracy of 10 cm from the LiteMapper 5600 system. The 1 meter resolution CHM was segmented in eCognition with a D-value of 0.23 (77% accuracy). A total of 312 trees were matched on the CHM with TLS and field measurement.

The Airborne LiDAR was used to validate the field and TLS height measurements. The Airborne LiDAR estimated 78.56% of field measured tree height correctly, while it correctly estimated 93.24% of tree height measured using the TLS. The variation in tree height measurements could be due to differences in the dates of data acquisition especially in Plot 8 and 10 where field and TLS height were slightly higher than the Airborne LiDAR measured height. The Airborne LiDAR was acquired on 23 July 2013, mean while field and TLS data was collected between September and October 2015 with a period more than two years which could be potential for changes in tree height where reforestation has taken place.

The process of the creating CHM involves creation of DTM and DSM which often involves TIN. The processes introducess uncertainity, especially in individual tree identification. The point clouds in the Las/Laz format are triangulated using TIN to raster DEM and CHM, the accuracy was therefore enhanced and the quality improved by the LiDAR point density and the selected spatial resolution of the CHM. The standard CHM contained pits and holes that could be associated with a combination of factors ranging from data acquisition to post processing (Ben-Arieet et al., 2009). Persson et al., (2002) also explained that due to penetration of the laser pulse to the branches of trees makes returns that are not considered as first return on the CHM . These pits and holes were then removed using the pit free algorithm of (Khosravipour et al., 2014). The pitfree algorithm was evaluated with the 3x3 mean and gaussian filters in (Ben-Arie et al., 2009).

The canopy height model was then segmented using eCognition software with multi resolution and watershed segmentation algorithms. The segmentation was aimed at delineating the crowns of the emegent layer for the purposes of height measurement. The segmentation obtained an acurracy better than obtained in (Asmoro, 2014) with a D value 0.2325 (77% accuracy) when compared with D value of 0.48 (52% accuracy).

5.3. Tree Above Ground Biomass (AGB)

The AGB for the individual trees was calculated using the allometric equation developed by Chave et al., (2005), which requires tree DBH, height and wood density as an input. The wood density (REDD, 2012) specified for Asia and South Eastern Asia was adopted instead of the specific tree species wood densities as the focus was to assess sensitivity of AGB to height. This was in line with the objectives of the study that were aimed at assessing the accuracy of tree height measurement and its sensitivity to AGB.

AGB was calculated for 312 individual trees obtained from 26 plots using tree height from field measurement, TLS and Airborne LiDAR. DBH measured from the field was used in the allometric equation for the estimation of AGB. The total amount of AGB calculated was 146.33 Mg for field measured height, 170.86 Mg for TLS measured height and 179.85 Mg for the Airborne LiDAR measured tree height. This show great variation in the amount of AGB from different height measurement methods, how much tree biomass could be lost due to the errors associated with tree height measurement from field and TLS where Airborne LiDAR measurement are used as the standard.

Based on the Airborne LiDAR height as the most accurate measurement, significant amount of biomass is lost when other measurements were used especially 18.6% of AGB is lost when field measurement of tree height are used as an input to the allometric equation. Field measurement underestimates tree height by approximately ±3.12 meters standard error with an R^2 of 0.61 when field height was validated with the Airborne LiDAR measured height. Meanwhile the TLS measured height underestimates tree height by ±1.15 m standard error and consequently underestimation of the AGB by 4.99% when compared with the AGB calculated using the Airborne LiDAR CHM based tree height.

Given that the Airborne LiDAR system as the most accurate tree height measurements, both ALS and TLS are having a weak relationship or correlation with the field height measurement: thus, R^2 0.61 and R^2 0.61. While Airborne LiDAR and TLS tree height measurements are very close with high correlation or R^2 = 0.91. This is attribute to that fact that, TLS is filling the gap between ALS and field measurement (Srinivasan et al., 2015b). It was also noted that the allometric equation that was used was a general equation that transfers error as well (Hunter et al., 2013). The allometric equation used was not the a geographical area specific equation and therefore there could be potential errors that could be associated in the final AGB measurement, but the focus of this study was mainly on the tree height errors and how AGB is sensitive to these height measurement variations due to error.

5.4. Carbon stock estimation

The carbon stock was calculated from the amount of AGB. Carbon is approximately 50% of the amount of tree AGB (IPCC 2007). Based on the AGB, there was also significant difference between the carbon stock from field measurement, TLS and Airborne LiDAR. Field measurement underestimated carbon more than the TLS measurement in comparison to the Airborne LiDAR, which was used as the standard measurement.

In this study, the mean carbon stock per tree was 0.22 Mg for field height measurement, 0.26 Mg for TLS height while Airborne LiDAR was 0.27 Mg per tree. Most of the studies that carried out carbon stock mapping focused on the general carbon maps for the whole forest (Asmoro, 2014; Karna et al., 2013) while this study focused on the individual tree to understand the variation in the carbon stock from different measurements of the tree height.

5.5. Errors and sources of errors.

Most of the instruments and methods used to measure height have a certain amount of error that propagates in to the biomass calculation. The field height measurement is associated with errors that originate from the expertise and the experience of the personnel who are doing the measurement, tree canopy structure that prevents the measurement of the top most part of the tree, random error associated with the measurement instrument. The errors may be observed in the DBH and height measurement.

Chave et al., (2004) explained that the source of error in AGB and carbon stock estimation could be the minimum sample plot size required. However in this study, the focus was more on the errors associated with tree height measurement. In Ayer Hitam tropical forest, tree crowns were mixed, with emergent trees that have crowns that are difficult to be seen for the purpose of tree height measurement (Figure 4-3b) as was also observed in (Asmoro, 2014).

The forest contained various tree species with varying crown projections, tree stand orientation (Figure 5-5) and different layers of trees and massive understory. This coupled with the terrain could significantly introduce errors in the field tree height measurement

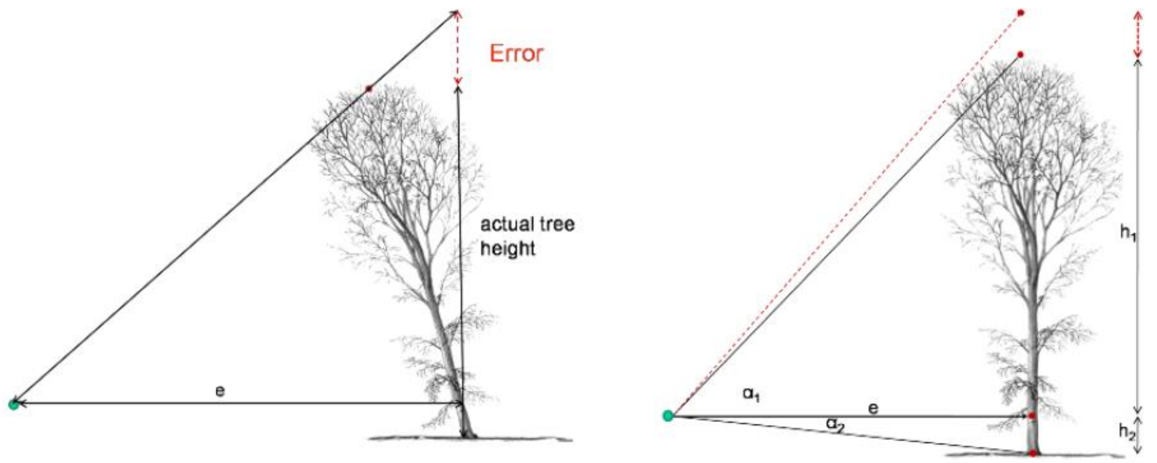


Figure 5-5: Error in tree height measurement
Source: (Asmoro, 2014)

The TLS height was measured after registration and processing of the scanned plots. Errors are associated with every stage especially setting up of the TLS in the field with the appropriate roll and pitch, scan project set up, undergrowth alongside with tree density that influences occlusion within the plot, point cloud saturation and positioning when the TLS is used without an external high accuracy GPS system. There are also errors associated with the Multi station adjustment (MSA) where all the scan positions are georeferenced to form the 3D of the plot. Tree detection and extraction also contain errors as they are reliant on the expertise carrying out the extraction. After tree extraction which is usually involves judgements on the exact tree crown, manual height measurement is done in the RiSCAN pro software and this potentially causes errors. Prasad, (2015) also identified errors associated with occlusion, overlapping crowns, and the subjectivity of manual tree height measurement.

Maas et al., (2008) also reported occlusion as one of the challenges and the sources of error for tree height measurement from the TLS in a study that also indicated achievement of low accuracies for height measurement using the TLS. The occlusion also potentially leads to the underestimation of tree height when cylinder method is applied since it's not clear whether the tree top is the actual top of the tree. This was the same case during the data collection where there were trees with DBH less or equal to 10 cm with their crowns below the trees that were measured and therefore it was there crowns scanned instead of the measured trees. This therefore was one of the sources of error for the TLS Height measurement. Despite the reported challenges, of which most of them were in temperate forest, the results obtained from Ayer Hitam tropical low land forest prove to be acceptable and accurate when compared with Airborne LiDAR for the individual trees.

Airborne LiDAR was regarded as the standard measurement for height for this study to validate the field and TLS height measurements. The Airborne system has been reported to collect data with 10 cm accuracy. The data that was obtained was further processed in various software. The Airborne LiDAR data was processed using the LP360 software from xyz files to Las files. The las files were further processed in LasTools to produce the DTM and DTM which were triangulated for the rasterized 1 m x 1 m resolution CHM. The CHM was then segmented for individual tree crown identification, which required field measured trees with their coordinates. The coordinates were collected from a geotagged images of the individual trees as well as verification from the TLS scanned data. Therefore, errors could emerge from identification of different tree peak for another due to shift in tree location. The tree identification on the CHM was enhanced in accuracy by using the TLS measurements and the position of the individual trees within the plot. The centre of the plot were collected using the MobileMapper GPS, with the bearing of the second scan position from the central scan. This enabled the determination of the individual tree position within the plot, thus measurement could improve the accuracy from the geotagged photos.

Errors in the estimation of AGB may also arise from the allometric equations or model selected. In this study, an allometric equation developed by (Chave et al., 2005) was adopted. However, the main aim of this study was to test the sensitivity of AGB to height errors. Measured tree height was varied while the DBH and the wood density in the tree allometric equation kept constant. The height errors could potentially affect the amount of AGB and consequently carbon stock (Basuki et al., 2009). Height was the only input that was changed in the allometric equation, this implies that the changes in the AGB that resulted were due to changes in the height not the errors of the allometric equation.

Height measurement errors could also arise from slope which affects the projection of the crowns and hence the top of the tree, what may be considered as the actual treetop may be affected by the slope orientation. Khosravipour et al., (2015) observed that slope potentially has influence on tree height. The highest point in a crown from downhill may be considered as a false local maxima for tree height estimation. This despite the findings, indicates the effects of CHM distortion on tree top in most parts depends on crown shape, tree species, with Scots Pine reported as vulnerable to systematic error. This though was evident in tree stand structure in the slop parts of the Ayer Hitam, however, this study was not focused on species specific observations as the focus was on the general tree height measurement.

GPS errors also affect the accuracy of height measurements. The GPS errors affect the identification and matching of trees on the Airborne LiDAR CHM with the trees that are measured from the field. Based on the operationalization of the Airborne LiDAR and the terrestrial measurements (Figure 4-13), Airborne LiDAR observes the crown and the position of the crown has to be confirmed by the exact location of the individual tree. In a situation where a wrong crown is identified for another tree or when a lower part of the crown is identified as the top most part of the trees due to displacement, the height measurement error is introduced. This happens due to accuracy of the GPS used in the field to obtain the control location of the sampled trees from the plot. In order to obtain the exact and top most part of the tree in this study, a standard accuracy MobileMapper GPS with ArcPad software was used to obtain the centre of plots that has an accuracy of 1-3 meters (Hunt & Dinterman, 2014), then the plots were scanned using the RIEGL VZ-400 that offer accurate position of the trees in a point cloud with four scan positions. The plots were delineated on the CHM since their radius were known. The bearing of the second scan position from the central scan position was measured, out of four scan positions in a plot and the angle of placing the third and fourth scan position known from the centre of the plot. Relative location of trees can be measured using the number tags and their position on the TLS scan as well as the Airborne LiDAR CHM. Segmentation of the crown was done and then the maximum height value represented in the pixel was selected (Jakubowski et al., 2013) This particularly minimised the risk of choosing a branch pixel to extract height information from the CHM. Therefore, the GPS associated errors were minimised since a number of methods were used in order to identify a particular tree.

5.6. Sensitivity Analysis

A total of 312 trees were measured using Leica DISTO 510, TLS and Airborne LiDAR. The error of the field measured tree height and TLS were quantified using the Airborne LiDAR. The results revealed that Leica DISTO measured tree height with ±3.12 m standard error and RMSE of 4.20 m while the TLS measured the same trees with ±1.62 m standard error and RMSE of 1.33 m. The actual height measurement were first used to estimate AGB and consequently carbon stock for the trees from the field, TLS and Airborne LiDAR in an allometric equation with constant DBH that was measured from the field and the wood density. The height measurements from field and TLS were then varied based on the measurement errors that were quantified.

The field measured height was varied by ±4 m while the TLS measured height was varied by ±1.5 m. Then the AGB was calculated using the adjusted heights from field and TLS. There was significant variation in the amount of AGB for field measurement (Figure 4-14), TLS (Figure 4-15) and when all the actual height measurements were also assessed as indicated in Figure 4-16 of which Airborne LiDAR as the standard estimated more AGB than the field and TLS measurements. The results are attributed to the capabilities of the different methods when used for tree height measurement as shown in Figure 4-13 and Figure 5-3 for field height measurement specifically in areas with slopes.

Therefore, AGB is sensitive to errors in tree height measurement. The sensitivity analyses carried out based on the errors from the measurements of tree height shows that the AGB is significantly sensitive to the changes in tree height. Errors in the measurements therefore affect the amount of Biomass. The sensitivity of the mount of AGB to tree height was assessed by varying the tree height measurements in the allometric equation with a constant DBH and wood density. Calders et al., (2015) selected trees and carried out a sensitivity analysis but the focus was reconstruction using the Quantitative Structure Models (QSM) models and TLS with different parameters and eventually obtained the AGB, meanwhile, in this study trees were selected to carry out sensitivity of AGB to the errors associated with tree height measurement as the only parameter where the other variables considered constant.

Raumonen et al., (2015) used sensitivity analysis tool to assess the effects tree extraction parameters to stem locating process in a QSM for individual trees using TLS. In study of Ayer Hitam forest, sensitivity analysis method was mainly used to assess the effect of tree height measurement errors to AGB as opposed to Raumonen et al., (2015) although the sensitivity analysis method was used.

5.7. Relevance to the REDD+ MRV

REDD+ MRVs require accurate data in order to obtain reliable results for various programs. The REDD+ has been implemented in tropical countries where tropical forests exist and many tropical countries are in the process of developing strategies for the implementation of the program. Using the methods in this study, would offer potential to obtain accurate results that can be used for the various projects under the program, especially for measurement of forest carbon and decision to choose the method for ground truth data acquisition. The methods used in this study could contribute towards the forest monitoring systems that has been emphasized in the REDD+ program. Hence accurate measurement of the forest carbon stock and changes, credits (REDD, 2012) where economic incentives are issued for carbon sequestration based on the measurement results among others at national level in the participating countries. This contributes to the action towards the climate change problem.

5.8. Limitation of the Research

The GPS error was a limitation in terms of the accuracy that could be obtained since the actual position of the tree and the overall centre of the plot was required to be highly accurate to ensure accurate measurements of the tree height from all the methods.

During the field work in Ayer Hitam tropical forest in Malaysia, it was rainy season. The tropical monsoon rains were occasionally delaying the field work, especially the scanning of the plots using the TLS.

The terrain in Ayer Hitam is very rugged with steep slopes. This was a limitation to setting up of the sample plots. The terrain is coupled with the massive understorey which required some clearance to minimise occlusion during the scanning of the plots using the TLS.

Time was a limiting factor, especially during the field work, data processing mainly the TLS and the Airborne LiDAR required much time to register plots, detect, extract and measure tree heights and DBH from the various trees within the 26 plots that were sampled. Processing and matching trees on ALS also consumed a lot of time that was limited.

TLS equipment was heavy approximately 27 Kgs and the camera approximately 3 kilograms were limitation to carry and move with in the forest from one sample location to another.

Airborne LiDAR has a limitation for capturing the top of sub layers in the study area. Most trees considered for the analysis in this study were the top and emergent trees from the tropical forest setting. Hence there was a limitation of getting data of trees that are directly below the emergent trees since the returns were recorded from the top most layers.

6. CONCLUSION AND RECOMMENDATION

6.1. Conclusion

LiDAR Technology both terrestrial and Airborne, offers substantial capability for mapping and estimating of the amount of above ground biomass and consequently the carbon stock. This is essential for the initiatives of the REDD+ programs towards the climate change problem. Quantifying the amount of AGB requires accurate measurement of the tree parameters like height. In this study, the accuracy of LiDAR both airborne and terrestrial were assessed alongside with the field measurements using the Leica DISTO 510 laser ranger, for measuring tree height. The tree height measurements were then used in the allometric equation to assess the AGB and Carbon stock.

The quantified errors were used in a scatter plot to assess the sensitivity analysis of the AGB to tree height changes. Tree height measurement from the field proved to be less accurate compared to the TLS measurement with Airborne LiDAR CHM considered as the standard measurement technique. In terms of the accuracy, the correlation coefficients for the relationship between field height and LiDAR was 0.78 (R^2=0.61 and RMSE=4.20 m), while the correlation coefficient for TLS and LiDAR was 0.96 (R^2=0.91 and RMSE = 1.33 m), field and TLS was 0.79 (R^2=0.62 and RMSE =3.07 m). The results show that TLS and Airborne LiDAR are highly related compared to Airborne and field as well as field and TLS. The relationship between TLS measured height and field measurement were also assessed, despite their respective relationship with Airborne LiDAR, where they both resulted in R^2 of 0.61, they are correlated with a coefficient of 0.79.

The results are promising to decide on the Airborne LiDAR to be the most accurate for tree height measurement. This means that, the method can be applied in other low lying tropical forest despite that field measurement still possess a challenge, especially when the crown cannot be viewed clearly.

The following are the answers to research questions of this study:

What is the difference between the accuracy of the tree height from Field measurement, TLS and Airborne LiDAR?

The study revealed that there was a significant difference between the accuracy of tree height measured from the field, Terrestrial Laser Scanning and Airborne LiDAR as methods to measure tree height. The Airborne LiDAR was considered as the most accurate and a standard for validation of the tree height measurement as, it views the tree top from above with pulses that reach the ground. The ground and the top of tree (from the CHM) offers the accurate measurement of the tree height as opposed to field measurement and TLS that do not see the top of the tree which is required to accurately measure the tree height. The study in Ayer Hitam tropical forest found out that the RMSE for field measurement was 4.20 (21.44%), this means that 78.56% of tree height was accurately measured using Leica DISTO 510 when field measurement was validated using Airborne LiDAR, meanwhile, RMSE of 1.33 (6.76%) meaning 93.24% of tree height was accurately measured using TLS when compared with Airborne LiDAR. This implies that the TLS and Airborne LiDAR are still more accurate than the field measurement.

Based on the statistical significance, the null hypothesis (H_0) which stated that there was no difference in the accuracy of tree height measurements between field, TLS and Airborne LiDAR was rejected and alternative hypothesis (H_1) was considered since there was a significant difference in the height different height measurements using the three methods.

What is the amount of biomass from selected trees using the height measurements from Field, TLS and Airborne LiDAR with their different accuracies?

The amount of AGB and Carbon stock for individual trees were calculated using an allometric equation with height measured using the three different techniques. The study results revealed that, there was a significant difference in the amount of AGB and carbon stock from the three different height measurements. The results showed that field measured AGB was 146.33 Mg for the sampled trees which represents 85.55% of the AGB measured from Airborne LiDAR, meanwhile TLS measured AGB was 170.86 Mg for the same sampled trees which represents 95.02% of the AGB measured from Airborne LiDAR which was 179.85 Mg. Consequently the carbon stock measured from the different methods resulted in to a significant difference between the field measurement, TLS and Airborne, where by the carbon stock for field measurement was 68.77 Mg, TLS = 80.31 Mg and Airborne LiDAR = 84.53 Mg for all the 312 trees that were used for the analysis. The results therefore mean that, a lot of AGB and carbon stocks are under estimated when field measurements are considered as the truth data to validate Airborne LiDAR. Basing on the statistical significance of the results, the null hypothesis (H_0) which stated that there was no difference between the amount of AGB estimated from the height measurement from field, TLS and Airborne was rejected and the alternative hypothesis (H_1) considered.

What are the effects of errors of height measurements on biomass/carbon estimation using Field Measured height and Terrestrial Laser Scanning?

The errors associated with the height measurement from field and TLS were quantified using the Airborne LiDAR as the most accurate technique. It was revealed that a considerable amount of biomass is underestimated from the field measurement and TLS. Therefore, there are potentially effects of errors associated with tree height measurement on the amount of AGB and carbon stock. AGB was proved to be sensitive to the changes in the tree height due to the errors associated with the measurement.

Basing on the findings, it was concluded that there were errors associated with tree height measurement from field and TLS and therefore these errors have significant effect on the amount of AGB and consequently carbon stock since tree height is essential for biomass estimation.

6.2. Recommendations

Use of the TLS with an external GPS system most notably a Differential GPS (DGPS) is highly recommended to enhance the accuracy of the positions of the centre of the plot, trees as well as integration of the TLS data with global coordinate system where the point clouds from the TLS can be fused with Airborne LiDAR for further estimation of the tree height.

Use of Airborne LiDAR with high point density would be recommended for future studies of this nature to increase the accuracy of the tree height measurement from the CHM so that LiDAR can be used as a standard for measurement of tree height in forests.

In this study, 312 trees were used to carry out the final analysis for the accuracy of tree height. It would be recommended to increase the number of samples so that the sensitivity can be further assessed.

The study focused on the assessment of the sensitivity of AGB to tree height with a general allometric equation and method of sensitivity analysis. It would be recommended that, species based allometric equation and other sensitivity methods be used to see further the influence of error associated with tree height measurement.

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APPENDICES

Appendix 1: Summary of the relationship between AGB from field, TLS and Airborne LiDAR

Summary Output:: ALS/Field height

Regression Statistics	
Multiple R	0.984807723
R Square	0.969846251
Adjusted R Square	0.969748981
Standard Error	0.107060875
Observations	312

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	114.2838454	114.2838454	9970.64527	9.1289E-238
Residual	310	3.553229618	0.011462031		
Total	311	117.8370751			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	0.008777067	0.007614413	1.152691169	0.249925235
Biomass-Airborne [Mg]	0.798381937	0.007995563	99.85311848	9.1289E-238

RMSE =0.1071 R^2 = 0.9698, Alpha = 0.05, (P-value< alpha), *Decision:* There is significant difference

Summary Output:: ALS/TLS height

Regression Statistics	
Multiple R	0.997340099
R Square	0.994687273
Adjusted R Square	0.994670135
Standard Error	0.054106019
Observations	312

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	169.9111631	169.9111631	58040.44726	0
Residual	310	0.907513003	0.002927461		
Total	311	170.8186761			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	-0.01351261	0.003848143	-3.511462168	0.000511838
Biomass-Airborne [Mg]	0.973484938	0.004040767	240.915851	0

RMSE =0.1071 R^2 = 0.9698, Alpha = 0.05, (P-value< alpha), *Decision:* There is significant difference

Summary Output: TLS height/Field height

Regression Statistics	
Multiple R	0.980842907
R Square	0.962052808
Adjusted R Square	0.961930398
Standard Error	0.12010192
Observations	312

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	113.365489	113.365489	7859.247492	2.7359E-222
Residual	310	4.471586067	0.014424471		
Total	311	117.8370751			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	0.022857163	0.008459151	2.702063387	0.007270533
Biomass-TLS [Mg]	0.81465318	0.009189297	88.65239699	2.7359E-222

RMSE =0.1071 R^2 = 0.9698, Alpha = 0.05, (P-value< alpha), *Decision:* There is significant difference

Appendix 2: Summary of relationship (t-Test) for AGB from field, TLS and Airborne LiDAR

t-Test: Paired Two Sample for Means

	AGB-Field [Mg]	AGB-Airborne LiDAR [Mg]
Mean	0.468990681	0.576432899
Variance	0.378897347	0.576504963
Observations	312	312
Pearson Correlation	0.984807723	
Hypothesized Mean Difference	0	
df	311	
t Stat	-10.1645579	
P(T<=t) one-tail	1.90754E-21	
t Critical one-tail	1.649767922	
P(T<=t) two-tail	3.81508E-21	
t Critical two-tail	1.967621133	

t-Test: Paired Two Sample for Means

	AGB-TLS [Mg]	AGB-Airborne LiDAR [Mg]
Mean	0.547636135	0.576432899
Variance	0.549256193	0.576504963
Observations	312	312
Pearson Correlation	0.997340099	
Hypothesized Mean Difference	0	
df	311	
t Stat	-8.823326261	
P(T<=t) one-tail	4.08317E-17	
t Critical one-tail	1.649767922	
P(T<=t) two-tail	8.16634E-17	
t Critical two-tail	1.967621133	

t-Test: Paired Two Sample for Means

	AGB-Field [Mg]	AGB-TLS [Mg]
Mean	0.468990681	0.547636
Variance	0.378897347	0.549256
Observations	312	312
Pearson Correlation	0.980842907	
Hypothesized Mean Difference	0	
df	311	
t Stat	-7.618599289	
P(T<=t) one-tail	1.55763E-13	
t Critical one-tail	1.649767922	
P(T<=t) two-tail	3.11525E-13	
t Critical two-tail	1.967621133	

Appendix 3: Summary of relationship for carbon stock from field, TLS and Airborne LiDAR

t-Test: Paired Two Sample for Means

	Carbon stock-Field [Mg]	Carbon stock-Airborne LiDAR [Mg]
Mean	0.22042562	0.270923462
Variance	0.083698424	0.127349946
Observations	312	312
Pearson Correlation	0.984807723	
Hypothesized Mean Difference	0	
df	311	
t Stat	-10.16455788	
P(T<=t) one-tail	1.90754E-21	
t Critical one-tail	1.649767922	
P(T<=t) two-tail	3.81508E-21	
t Critical two-tail	1.967621133	

t-Test: Paired Two Sample for Means

	Carbon stock-TLS [Mg]	Carbon stock-Airborne LiDAR [Mg]
Mean	0.257388984	0.270923462
Variance	0.121330693	0.127349946
Observations	312	312
Pearson Correlation	0.997340099	
Hypothesized Mean Difference	0	
df	311	
t Stat	-8.823326261	
P(T<=t) one-tail	4.08317E-17	
t Critical one-tail	1.649767922	
P(T<=t) two-tail	8.16634E-17	
t Critical two-tail	1.967621133	

t-Test: Paired Two Sample for Means

	Carbon stock-Field [Mg]	Carbon stock-TLS [Mg]
Mean	0.220426	0.257388984
Variance	0.083698	0.121330693
Observations	312	312
Pearson Correlation	0.980843	
Hypothesized Mean Difference	0	
df	311	
t Stat	-7.6186	
P(T<=t) one-tail	1.56E-13	
t Critical one-tail	1.649768	
P(T<=t) two-tail	3.12E-13	
t Critical two-tail	1.967621	

Appendix 4: Slope correction table

Slope (%)	Radius (m)	Slope (%)	Radius (m)	Slope (%)	Radius (m)
0	12.62				
1	12.62	36	13.01	71	13.97
2	12.62	37	13.03	72	14.00
3	12.62	38	13.05	73	14.04
4	12.62	39	13.07	74	14.07
5	12.62	40	13.09	75	14.10
6	12.63	41	13.12	76	14.14
7	12.63	42	13.14	77	14.17
8	12.64	43	13.16	78	14.21
9	12.64	44	13.19	79	14.24
10	12.65	45	13.21	80	14.28
11	12.65	46	13.24	81	14.31
12	12.66	47	13.26	82	14.35
13	12.67	48	13.29	83	14.38
14	12.68	49	13.31	84	14.42
15	12.69	50	13.34	85	14.45
16	12.70	51	13.37	86	14.49
17	12.71	52	13.39	87	14.52
18	12.72	53	13.42	88	14.56
19	12.73	54	13.45	89	14.60
20	12.74	55	13.48	90	14.63
21	12.75	56	13.51	91	14.67
22	12.77	57	13.53	92	14.71
23	12.78	58	13.56	93	14.74
24	12.79	59	13.59	94	14.78
25	12.81	60	13.62	95	14.82
26	12.82	61	13.65	96	14.85
27	12.84	62	13.68	97	14.89
28	12.86	63	13.72	98	14.93
29	12.87	64	13.75	99	14.97
30	12.89	65	13.78	100	15.00
31	12.91	66	13.81	101	15.04
32	12.93	67	13.84	102	15.08
33	12.95	68	13.87	103	15.12
34	12.97	69	13.91	104	15.15
35	12.99	70	13.94	105	15.19

Appendix 5: Data collection sheet

DATA COLLECTION SHEET (AYER HITAM TROPICAL RAIN FOREST RESERVE, MALAYSIA

Name of recorder.. Date...

<table>
<tr><td rowspan="2">Sample Plot No.</td><td rowspan="2">GPS Coordinates</td><td>X:</td><td rowspan="2">Grid cell No.:</td><td>Slope (%):</td><td colspan="2">Undergrowth</td><td rowspan="2">Crown Cover (%)</td></tr>
<tr><td>Y:</td><td>Bearing of Scan Position:</td><td>Y</td><td>N</td></tr>
</table>

Tree No.	Species	DBH (cm)	Height 1 (Leica)	Height 2 (Haga)	Height 3 (TruPulse)	Crown Diam.(m)
1						
2						
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Appendix 6: Sampled trees with their GPS coordinates and height measurements

Plot No.	Tree No.	Latitude	Longitude	Species	DBH Field [cm]	DBH TLS [cm]	Height Field [m]	Height TLS [m]	Height ALS [m]
1	1	3.0064629	101.644568	*Macaranga spp.*	10.00	9.50	9.00	7.61	10.30
	3	3.0063535	101.6445782	*Sugi*	16.00	16.40	9.00	12.10	13.65
	4	3.0063741	101.6445532	*Litsea spp.*	22.00	22.10	18.00	10.94	11.41
	5	3.0063653	101.6445102	*Syzygium spp.*	23.00	23.20	14.00	15.32	17.67
	6	3.0063639	101.6444787	*Carallia spp.*	29.00	28.50	19.00	15.68	16.04
	7	3.0063705	101.6444708	*Syzygium spp.*	38.00	38.40	20.00	14.62	15.73
	8	3.0063869	101.6444557	*Macaranga spp.*	20.00	20.10	22.00	16.52	17.10
	9	3.0064194	101.6445216	*litsea costata*	30.00	24.50	17.00	13.91	13.96
	10	3.0064042	101.6445211	*Gironniera spp.*	32.00	32.40	17.00	15.98	17.10
	16	3.0064653	101.6446028	*Sugi*	14.00	13.50	16.00	11.43	12.67
	17	3.0064891	101.6445591	*litsea costata*	42.00	42.20	16.60	17.28	18.92
	21	3.0063997	101.6444414	*Garcinia spp.*	11.00	10.50	8.00	7.85	8.43
2	1	3.0067916	101.6398781	*Gilha spp.*	150.00	108.00	27.00	37.70	37.68
	2	3.0068502	101.6399387	*Streblus elongatus*	14.00	28.90	13.60	19.34	20.18
	4	3.0068272	101.6399835	*Palaquim gutta*	30.00	29.00	18.00	16.79	17.73
	8	3.0068049	101.639921	*Artocarpus s.*	32.00	31.70	20.00	13.94	15.52
	12	3.0068161	101.6399402	*Streblus elongatus*	18.00	17.90	11.00	15.62	16.48
	13	3.0068384	101.6400136	*Artocarpus s.*	51.00	52.00	18.00	23.32	23.51
	16	3.0068347	101.6401206	*Macaranga gigantea*	30.00	29.80	14.00	16.02	16.55
	19	3.0068628	101.6400815	*Nyatoh Nongka k.*	51.00	49.70	18.00	20.66	20.95
	29	3.006706	101.6400119	*Endospermum d.*	31.00	31.50	22.00	21.15	22.59
	31	3.006867	101.6400041	*Streblus elongatus*	27.00	27.20	16.00	15.02	16.23
	32	3.0067131	101.6400744	*Streblus elongatus*	33.00	32.80	15.00	13.53	13.65
	33	3.0067364	101.6400747	*Diospyros argentea*	11.00	11.20	8.00	11.87	12.49
	34	3.0068013	101.6401432	*Endospermum d.*	24.00	24.40	15.00	18.40	18.92
3	2	3.0136251	101.6429704	*Hopea sulcata*	28.00	18.20	22.00	17.86	18.77
	3	3.0136409	101.6429227	*Streblus elongatus*	46.00	41.10	20.00	18.50	19.83
	5	3.0136209	101.6429163	*Calophyllum spp.*	20.00	19.40	15.00	13.55	15.93
	6	3.0136053	101.6429464	*Knema spp.*	18.00	15.70	17.00	15.90	17.89
	7	3.0135966	101.6429228	*Litsea spp.*	11.00	10.90	12.00	15.88	17.88
	8	3.013587	101.6429333	*Streblus elongatus*	27.00	24.30	18.00	17.25	18.53
	9	3.0135746	101.6429403	*Hopea sulcata*	23.00	22.10	12.00	13.44	19.78
	10	3.0135591	101.642929	*Merlimau*	11.00	10.90	10.00	12.81	19.06
	11	3.0135608	101.6428963	*Streblus elongatus*	14.00	12.80	10.00	12.62	15.75
	12	3.0135702	101.6429132	*Lithocarpus spp.*	37.00	35.70	18.00	15.80	17.91
	13	3.0135518	101.6429052	*Shorea accuminata*	52.00	52.20	20.00	16.01	19.79
	16	3.0136527	101.6429591	*Syzygium spp.*	17.00	17.30	10.00	7.35	11.93
	19	3.0136486	101.6430392	*Perpi melanti*	45.00	44.90	28.00	23.03	24.60
	23	3.0136492	101.6430964	*Shorea macroptera*	37.00	37.10	20.00	13.67	24.05
	24	3.0136343	101.6431095	*Mendong*	13.00	12.10	13.00	21.36	23.89
	25	3.0136057	101.6430381	*Gluta spp.*	59.00	58.80	38.00	28.71	29.49
	26	3.0136241	101.643053	*Calophyllum spp.*	27.00	25.10	18.00	20.89	22.29
	27	3.013628	101.643087	*Streblus elongatus*	14.00	14.20	15.00	17.92	19.43
	29	3.0136687	101.6429131	*Hopea sulcata*	31.00	30.80	18.00	22.29	22.81
	30	3.0135617	101.6429843	*Shorea accuminata*	56.00	50.90	24.00	28.62	30.89
4	1	3.013222	101.64605	*Scaphium m.*	27.00	26.70	14.00	21.18	22.36
	2	3.013196	101.64604	*Scaphium m.*	34.00	34.10	21.00	28.51	25.38
	3	3.013195	101.645962	*Streblus elongatus*	36.00	36.40	14.00	20.76	25.03
	4	3.013207	101.645951	*Streblus elongatus*	33.00	32.60	14.00	20.76	25.03
	6	3.013264	101.646023	*Streblus elongatus*	16.00	16.10	10.00	8.93	18.51

	9	3.013263	101.645933	*Palaquim spp.*	28.00	27.50	13.00	17.14	18.83
	11	3.013273	101.645969	*Cratoxylum spp.*	34.00	33.50	15.00	26.38	28.23
	18	3.013294	101.646048	*Pellacalyx axillaris*	16.00	15.90	16.00	18.44	18.85
	19	3.013363	101.646013	*Streblus elongatus*	19.00	18.70	9.00	14.23	15.25
	21	3.013341	101.646098	*Elaeocarpus spp.*	29.00	28.90	19.00	18.86	21.91
	23	3.013276	101.646036	*Streblus elongatus*	23.00	23.10	17.00	18.48	19.57
	25	3.013318	101.646097	*Endospermum d.*	52.00	52.30	18.00	17.50	25.21
	32	3.013238	101.646059	*Streblus elongatus*	52.00	52.30	17.00	21.48	22.41
5	1	3.019508	101.645975	*Ficus spp.*	12.00	11.60	10.00	13.52	17.03
	2	3.019526	101.64601	*Palaquim gutta*	33.00	30.40	16.00	23.60	23.27
	5	3.019517	101.646041	*Elaeocarpus spp.*	18.00	18.20	14.00	15.36	17.11
	6	3.019501	101.646056	*Minyak berok*	11.00	11.30	8.00	9.01	16.03
	7	3.019455	101.64586	*Endospermum d.*	39.00	36.50	27.00	25.35	26.94
	8	3.019474	101.645857	*Macaranga gigantea*	23.00	20.30	30.00	24.08	24.79
	9	3.019502	101.645887	*Scaphium spp.*	57.00	52.30	32.00	20.10	21.47
	11	3.019573	101.645941	*Palaquim gutta*	24.00	23.80	18.00	20.10	20.78
	12	3.019536	101.645878	*Byera costulata*	69.00	68.70	30.00	17.09	26.63
	13	3.019518	101.645896	*Lithocarpus spp.*	38.00	38.40	15.00	25.04	25.34
	14	3.019512	101.645845	*Litsea spp.*	33.00	31.90	23.00	23.23	23.36
	15	3.019542	101.645924	*Lithocarpus spp.*	27.00	21.90	27.00	16.76	17.97
	16	3.019538	101.645914	*Knema spp.*	21.00	21.60	22.00	23.00	23.44
	17	3.019538	101.645932	*Elaeocarpus spp.*	63.00	60.90	28.00	20.41	28.87
	18	3.019552	101.645973	*Litsea spp.*	25.00	24.50	14.00	22.36	25.54
	19	3.01954	101.646024	*Mata keli*	12.00	11.70	14.00	14.64	17.02
	20	3.01954	101.646024	*Mata keli*	30.00	29.50	16.00	11.92	19.26
	22	3.019435	101.645885	*Ixonanthes icosandra*	17.00	17.40	15.00	14.27	17.02
6	1	3.0159245	101.6481985	*Burseraceae*	54.00	53.70	23.00	19.68	20.88
	4	3.0158512	101.6482347	*Endospermum d.*	31.00	30.80	13.00	21.23	23.30
	6	3.015862	101.6482057	*Endospermum d.*	17.00	17.30	10.00	21.51	21.93
	13	3.015889	101.6482385	*Ochanostchys a.*	10.00	10.20	6.00	10.41	11.88
	14	3.0158986	101.6482599	*Diospyros spp.*	24.00	24.20	12.00	17.26	16.25
	15	3.0158971	101.648253	*Delek*	12.00	12.10	12.00	13.52	15.25
	16	3.0159614	101.6481834	*Castanopsis spp.*	44.00	44.40	18.00	24.24	23.42
	18	3.0159516	101.6482505	*Streblus elongatus*	28.00	27.70	18.00	17.84	19.12
	19	3.0159969	101.6482602	*Macaranga spp.*	23.00	23.30	15.00	14.96	15.96
	20	3.0159915	101.6482058	*Endospermum d.*	21.00	20.60	13.00	21.24	22.67
	22	3.0159655	101.6482222	*Pouteria malaccensis*	23.00	22.50	12.00	19.01	20.51
	24	3.0158673	101.6482276	*Merlimau*	15.00	15.00	13.00	14.25	15.75
	25	3.0158618	101.6482865	*Diospyros spp.*	15.00	15.30	12.00	14.70	14.95
	26	3.0159352	101.6483043	*Koompassia m.*	34.00	33.90	19.00	16.56	16.54
	29	3.015887	101.6483855	*Shorea macroptera*	34.00	34.30	24.00	25.31	25.82
	30	3.0157901	101.6482486	*Lithocarpus spp.*	28.00	27.90	26.00	23.36	24.91
7	4	3.011771	101.646487	*Litsea costata*	15.00	15.20	10.00	11.56	12.11
	5	3.011771	101.646478	*Litsea costata*	16.00	15.50	12.00	13.34	14.53
	7	3.011729	101.646496	*Syzygium polyanthum*	22.00	21.60	16.00	19.16	19.53
	8	3.011719	101.64642	*Syzygium polyanthum*	27.00	27.10	20.00	14.07	20.52
	9	3.011735	101.646417	*Syzygium polyanthum*	21.00	21.31	18.00	14.16	19.82
	13	3.011703	101.646454	*Syzygium polyanthum*	17.00	16.61	14.00	14.11	15.93
	14	3.011718	101.64647	*Syzygium polyanthum*	15.00	14.50	9.00	10.71	11.49
	20	3.011717	101.646549	*Silver timon*	13.00	12.80	13.00	15.82	16.27
	22	3.011736	101.646516	*Swintonia spp.*	35.00	34.60	18.00	22.38	22.24
	26	3.01176	101.646561	*Gironniera nervosa*	16.00	16.10	11.00	16.33	18.32
	31	3.011807	101.646533	*Syzygium polyanthum*	25.00	25.40	17.00	14.16	20.00

8	7	3.001055	101.64485	*Acacia auriculiformis*	34.00	33.90	6.00	6.17	10.80
	12	3.001165	101.64479	*Cinnamomum iners*	19.00	18.70	6.00	9.72	10.21
	13	3.001179	101.644794	*Cinnamomum iners*	18.00	17.60	6.00	8.49	10.71
	15	3.00111	101.64487	*Syzygium spp.*	11.00	11.20	6.00	6.28	7.47
	17	3.001127	101.644873	*Cinnamomum iners*	19.00	18.30	7.00	9.22	10.89
	20	3.001113	101.64496	*Shorea hypocra*	13.00	13.20	8.00	10.48	16.17
	21	3.00114	101.644934	*Shorea sumatranum*	10.00	9.50	8.00	10.12	13.56
	22	3.001122	101.644965	*Acacia auriculiformis*	42.00	41.50	15.00	11.22	16.48
	23	3.001092	101.644979	*Cinnamomum iners*	14.00	14.30	10.00	7.87	9.38
	24	3.001084	101.644952	*Cinnamomum iners*	15.00	14.70	9.00	10.82	13.03
	26	3.001112	101.644897	*Cinnamomum iners*	12.00	11.70	5.00	9.03	9.83
9	1	3.0233329	101.6676368	*Syzygium spp.*	12.00	11.70	8.00	13.65	15.79
	3	3.0233215	101.6676587	*Endospermum d.*	37.00	37.30	12.00	20.65	19.48
	5	3.0233092	101.6676529	*Herittiera spp.*	19.00	18.70	12.00	17.51	18.12
	6	3.0232876	101.6676239	*Endospermum d.*	36.00	36.20	18.00	20.21	20.60
	8	3.0233159	101.6675968	*Burseraceae*	23.00	23.40	12.00	15.43	16.56
	9	3.0233058	101.6675689	*Arthocarpus s.*	12.00	12.20	7.00	13.79	14.13
	12	3.023331	101.6675684	*Carallia brachiata*	22.00	21.90	12.00	16.18	16.79
	13	3.0233436	101.6675207	*Shorea parvifolia*	51.00	51.00	20.00	26.01	27.23
	14	3.0233421	101.6675867	*Syzygium spp.*	14.00	11.00	12.00	11.18	11.74
	15	3.023396	101.6675158	*Shorea parvifolia*	43.00	43.10	18.00	23.99	23.97
	16	3.0233502	101.6676768	*Shorea parvifolia*	38.00	37.80	17.00	13.43	14.61
	24	3.0233693	101.6675837	*Ochanostchys a.*	26.00	26.10	12.00	9.32	10.91
	28	3.0234148	101.6676136	*Endospermum d.*	45.00	44.70	14.00	19.79	20.40
10	4	3.0347736	101.6565763	*Acacia mangium*	32.00	31.80	14.00	21.00	19.56
	5	3.0348023	101.6565572	*Mollatus spp.*	10.00	10.00	10.00	11.43	11.41
	6	3.0348095	101.6566274	*Ixonanthes icosandra*	11.00	10.40	8.00	12.15	12.65
	15	3.0347814	101.6566558	*Elaeocarpus spp.*	32.00	31.00	12.00	14.71	15.36
	17	3.0348569	101.6567293	*Shorea bracteolata*	27.00	27.90	18.00	18.56	18.34
	19	3.0347293	101.6566389	*Diplospora m.*	19.00	19.70	7.00	8.22	9.05
	24	3.0347654	101.6566107	*Artocarpus rigidis*	10.00	10.00	10.00	10.92	11.92
	26	3.0347459	101.6566023	*Litsea costata*	26.00	28.80	14.00	14.68	15.20
	27	3.0347333	101.6566046	*Shorea bracteolata*	13.00	12.60	14.00	13.79	14.42
	28	3.0347165	101.6566019	*Shorea bracteolata*	20.00	20.90	12.00	13.47	13.54
	29	3.0347015	101.6566208	*Artocarpus rigidis*	11.00	11.80	10.00	10.93	10.76
	31	3.0347552	101.656747	*Elaeocarpus spp.*	27.00	26.40	10.00	14.17	13.66
11	1	3.0036307	101.6431223	*Lithocarpus spp.*	19.00	18.50	12.00	14.63	15.51
	2	3.0036829	101.6432139	*Artocarpus s.*	30.00	65.40	21.00	21.50	21.95
	7	3.0035258	101.6432039	*Gironniera nervosa*	23.00	23.60	14.00	19.87	20.51
	8	3.0035015	101.6432006	*Myrysticaceae*	27.00	26.90	10.00	19.83	20.17
	9	3.003582	101.6432926	*Artocarpus rigidis*	17.00	16.50	12.00	19.14	19.73
	10	3.003629	101.6432217	*Carallia brachiata*	28.00	27.90	13.00	17.92	18.27
	11	3.0036365	101.6432225	*Syzygium spp*	25.00	24.70	11.00	14.23	15.74
	12	3.0035562	101.6432739	*Gaham badak*	20.00	19.40	16.00	17.76	17.86
	17	3.003602	101.6432596	*Palaquim x.*	56.00	57.50	23.00	25.62	25.83
	21	3.0037036	101.6432217	*Sandoricum koetjape*	39.00	37.60	14.00	19.24	20.05
	28	3.0035651	101.6431152	-	28.00	25.50	16.00	19.23	19.82
	29	3.0035301	101.6431138	-	16.00	16.40	10.00	10.38	10.96
12	2	3.0049152	101.6414635	*Campnosperma spp.*	34.00	33.90	19.00	21.52	21.75
	10	3.0049423	101.641447	*Endospermum d.*	28.00	27.00	12.00	20.23	20.72
	11	3.0049786	101.6414472	*Xylopia ferruginea*	12.00	12.00	14.00	15.61	15.87
	12	3.0050072	101.6413305	*Elaeocarpus spp.*	11.00	10.20	15.00	17.63	17.98
	13	3.0050218	101.6413378	*Calophyllum spp.*	22.00	22.40	15.00	17.90	18.82

	14	3.0049456	101.641357	*Gargam badak*	13.00	13.60	9.00	11.00	13.37
	18	3.0050158	101.641367	*Ochanostchys a.*	10.00	10.00	10.00	11.51	11.81
	19	3.0051041	101.641478	*Endospermum d.*	26.00	25.00	22.00	21.40	21.66
	20	3.0049948	101.6414734	*Merlimau*	10.00	10.90	9.00	11.10	11.78
	21	3.0050534	101.6414482	*Madhuca utilis*	13.00	14.10	17.00	19.49	19.85
	22	3.0050717	101.6414789	*Madhuca utilis*	13.00	13.40	18.00	19.49	19.62
	24	3.0050036	101.6415002	*Nephelium meiingayi*	32.00	35.30	17.00	20.78	21.52
	31	3.0050367	101.6413778	*Herittiera spp.*	21.00	21.30	15.00	16.41	16.77
	32	3.0050882	101.6413997	*Xylopia ferruginea*	20.00	19.50	15.00	18.00	18.88
	33	3.0050522	101.6414205	*Dillenia spp.*	10.00	10.50	8.00	10.81	15.52
	40	3.0049806	101.6413889	*Myrysticaceae*	11.00	10.50	10.00	12.29	13.09
13	1	3.0046358	101.6441148	*Litsea costata*	12.00	12.80	6.00	9.47	10.58
	4	3.0046566	101.6440628	*Lauraceae*	33.00	34.20	13.00	20.02	21.71
	5	3.0046286	101.6440261	*Artocarpus s.*	34.00	36.70	15.00	19.76	20.53
	6	3.0046743	101.6440295	*Naphelium maingayi*	35.00	37.70	14.00	17.79	18.80
	7	3.0045742	101.6441394	*Aquilaria spp.*	14.00	14.00	10.00	15.30	15.68
	11	3.00462	101.6440528	*Gironniera nervosa*	14.00	13.60	11.00	11.72	11.87
	12	3.0046198	101.6441078	*Lithocarpus spp.*	13.00	11.30	10.00	11.90	10.61
	14	3.0045668	101.6440959	*Artocarpus s.*	22.00	22.00	15.00	15.70	15.81
	17	3.0046916	101.6441771	*syzygium polyanthum*	51.00	50.00	13.00	21.64	21.45
	18	3.0046894	101.6442045	*Memecylon spp.*	16.00	16.20	18.00	12.15	13.29
	19	3.0046019	101.6441442	*Ochanostchys a.*	15.00	12.90	13.00	10.84	10.40
	20	3.0046549	101.6441083	*Aquilaria spp.*	12.00	12.74	12.00	13.30	13.82
	22	3.0046745	101.6441445	*Elaeocarpus spp.*	19.00	19.10	10.00	13.26	15.59
14	1	3.020184	101.633323	*Blumeodendron spp.*	13.00	13.80	11.00	16.46	20.56
	2	3.020186	101.633286	*Lithocarpus spp.*	26.00	27.80	19.00	22.00	23.49
	4	3.020224	101.633316	*Streblus elongatus*	10.00	19.50	12.00	23.91	24.62
	7	3.020295	101.633361	*Ixonanthes icosandra*	20.00	19.60	12.00	16.45	19.73
	8	3.020309	101.633396	*Mentimun*	21.00	20.60	12.00	19.84	21.81
	10	3.020261	101.633491	*Palaquim gutta*	65.00	62.70	22.00	37.34	37.88
	11	3.02026	101.633516	*Naphelium spp.*	17.00	17.70	12.00	18.51	18.96
	12	3.020224	101.633513	*Tetebu*	32.00	32.70	21.00	24.62	25.01
	13	3.020216	101.633401	*Burseraceae*	30.00	29.80	14.00	19.89	20.43
	14	3.020205	101.633379	*Naphelium spp.*	21.00	20.89	15.00	22.95	23.34
	26	3.020118	101.63327	*Lithocarpus spp.*	36.00	38.00	25.00	24.33	25.80
15	1	3.018494	101.634145	*Aporusa spp.*	22.00	22.10	21.00	23.09	23.43
	3	3.018448	101.634098	*Kuping begi*	16.00	15.80	10.00	19.32	20.62
	11	3.018506	101.634089	*Streblus elongatus*	40.00	44.30	24.00	23.46	23.23
	13	3.01849	101.634107	*Hopea sulcata*	23.00	22.30	16.00	22.69	21.04
	14	3.018506	101.634123	*Burseraceae*	12.00	12.20	13.00	16.97	23.81
	15	3.018554	101.634063	*Streblus elongatus*	18.00	18.40	11.00	15.66	33.01
	18	3.018589	101.634104	*Hopea sulcata*	60.00	61.70	22.00	32.54	32.56
	25	3.01851	101.634191	*Rhodamnia cinerea*	26.00	26.00	14.00	22.89	28.80
	30	3.018494	101.634161	*Pentaspadon spp.*	36.00	36.00	10.00	28.68	29.14
	32	3.018518	101.634172	*Shorea macroptera*	19.00	19.60	16.00	19.12	25.56
	33	3.018525	101.634171	*Naphelium spp.*	19.00	18.80	10.00	15.65	25.56
	34	3.018536	101.634146	*Palaquim gutta*	18.00	18.30	12.00	17.42	25.91
	35	3.018552	101.634175	*Streblus elongatus*	15.00	15.70	13.00	14.00	25.40
	36	3.018564	101.634181	*Streblus elongatus*	19.00	19.20	12.00	19.42	25.35
	37	3.018584	101.634183	*Shorea accuminata*	66.00	65.00	22.00	27.01	27.91
	38	3.018498	101.634119	-	10.00	10.00	14.00	16.14	21.80
16	1	3.019539	101.633953	*Madhuca utilis*	15.00	15.40	12.00	15.40	15.86
	3	3.019498	101.633975	*Hopea sulcata*	28.00	24.00	19.00	24.16	25.65

	5	3.019528	101.633922	*Calophyllum r.*	25.00	25.20	15.00	18.32	18.26
	10	3.019529	101.63399	*Calophyllum spp.*	16.00	17.00	16.00	20.68	20.99
	11	3.019532	101.634001	*Dipterocapus crinitus*	28.00	30.70	20.00	28.02	28.25
	13	3.019581	101.633988	*Bedil lalat*	10.00	10.00	13.00	13.93	14.20
	16	3.019372	101.634058	*Shorea accuminata*	67.00	61.70	21.00	33.63	33.73
	18	3.01937	101.634024	*Naphelium spp.*	16.00	15.60	13.00	15.84	17.63
	19	3.019388	101.634093	*Anisoptera curtisii*	53.00	53.10	25.00	33.47	33.33
	21	3.019459	101.63392	*Syzygium spp.*	40.00	41.30	22.00	29.61	29.79
	22	3.019494	101.633953	*Bouea spp.*	10.00	10.50	7.00	9.66	10.69
	24	3.01947	101.634065	*Pouteria malaccensis*	46.00	44.80	19.00	19.20	19.78
	26	3.019417	101.634102	*Anisoptera costata*	16.00	15.90	16.00	18.00	18.98
	27	3.019441	101.634082	*Syzygium spp.*	24.00	24.20	15.00	18.21	19.29
	28	3.019501	101.634066	*Shorea accuminata*	25.00	43.40	21.00	29.29	29.20
17	1	3.034587	101.635929	*Macaranga spp.*	27.00	27.70	21.00	18.97	21.75
	3	3.03457	101.635936	*Macaranga spp.*	21.00	21.80	22.00	20.16	20.77
	5	3.034535	101.635929	*Elaeocarpus spp.*	27.00	26.40	19.00	18.00	18.24
	9	3.034534	101.635822	*Annonaceae*	23.00	22.60	20.00	19.76	20.89
	10	3.034584	101.635818	*Gironniera nervosa*	12.00	11.40	15.00	13.15	13.08
	12	3.034591	101.635805	*Rhodamnia cinerea*	17.00	17.10	14.00	16.39	15.77
	25	3.034677	101.635832	*Artocarpus spp.*	17.00	16.20	8.00	14.00	14.86
	26	3.03467	101.635866	*Endospermum d.*	24.00	25.80	9.00	14.82	19.45
18	2	3.033415	101.636445	*Lauraceae*	12.00	14.00	6.00	10.00	15.62
	3	3.033405	101.636471	*Burseraceae*	25.00	24.80	14.00	18.00	18.55
	4	3.033378	101.636443	*Porterandia a.*	27.00	26.80	12.00	14.10	15.32
	6	3.033378	101.636427	*Artocarpus s.*	68.00	64.00	16.00	20.00	20.43
	7	3.033404	101.636417	*Palaquim gutta*	19.00	18.90	13.00	12.60	15.62
	8	3.033408	101.636383	*Cyathocalyx spp.*	38.00	37.80	16.00	23.00	23.21
	17	3.033453	101.636329	*Metadina trichotoma*	41.00	40.00	18.00	18.00	19.99
	18	3.033488	101.636319	*Palaquim gutta*	21.00	22.00	16.00	19.00	20.90
	19	3.033485	101.636318	*Mentimun*	21.00	22.00	16.00	19.00	20.90
	20	3.033532	101.636427	*Artocarpus s.*	25.00	25.50	16.00	19.00	19.51
	21	3.033504	101.636372	*Memecylon spp.*	19.00	17.20	13.00	15.00	17.91
	33	3.033431	101.636462	*Palaquim maingayi*	15.00	15.60	13.00	17.00	18.40
	34	3.03344	101.636398	*Endospermum d.*	55.00	54.70	18.00	23.00	25.32
	36	3.033441	101.636265	*Endospermum d.*	56.00	55.60	17.00	22.00	23.14
19	2	3.014851	101.648177	*Shorea parvifolia*	42.00	42.80	25.00	28.00	27.60
	4	3.014831	101.648266	*Shorea accuminata*	47.00	46.80	20.00	28.00	28.77
	7	3.014969	101.648208	*Hopea sulcata*	45.00	44.20	22.00	25.00	25.32
	13	3.014912	101.648178	*Annonaceae*	19.00	19.00	16.00	15.50	17.15
	17	3.014983	101.648138	*Shorea macroptera*	40.00	38.00	27.00	26.70	26.77
	27	3.014893	101.64816	*Naphelium spp.*	24.00	23.70	21.00	19.70	20.21
	28	3.014868	101.648103	*Shorea leprosula*	53.00	53.50	17.00	27.00	27.02
	29	3.014848	101.648087	*Artocarpus rigidus*	23.00	24.00	18.00	16.90	17.03
	30	3.014859	101.648103	*Fagraea spp.*	66.00	65.60	19.00	26.00	26.30
	31	3.014885	101.648089	*Hopea sulcata*	26.00	25.20	27.00	31.00	30.70
	35	3.014795	101.64815	*Hopea sulcata*	37.00	35.00	22.00	18.00	19.72
	36	3.014793	101.648161	*Hopea sulcata*	34.00	33.80	22.00	18.00	19.72
20	1	3.013555	101.648451	*Shorea macroptera*	23.00	23.00	14.00	19.00	23.98
	2	3.013537	101.64848	*Myrysticaceae*	16.00	16.00	10.00	11.00	11.96
	3	3.013501	101.648469	*Xerospermum spp.*	25.00	25.00	17.00	17.00	17.63
	6	3.01349	101.648378	*Streblus elongatus*	22.00	22.00	13.00	12.30	13.33
	7	3.013538	101.648452	*Streblus elongatus*	31.00	31.00	13.00	18.00	18.92
	8	3.013509	101.648368	*Myrysticaceae*	15.00	15.00	15.00	19.00	20.60

	9	3.013537	101.648365	*Palaquim gutta*	32.00	32.00	22.00	24.00	24.32
	10	3.013618	101.648339	*Albizia splendens*	39.00	39.00	16.00	22.00	22.32
	12	3.013587	101.648349	*Artocarpus s.*	47.00	47.00	24.00	20.00	20.65
	14	3.01363	101.648435	*Ixonanthes icosandra*	58.00	58.00	22.00	22.00	23.71
	16	3.013639	101.648505	*Palaquim gutta*	20.00	20.00	16.00	16.88	22.53
	19	3.01361	101.648507	*Artocarpus s.*	42.00	42.00	20.00	24.00	24.33
	21	3.013585	101.64847	*Dipterocapus crinitus*	85.00	85.00	28.00	34.00	34.49
	24	3.013647	101.648408	*Shorea leprosula*	44.00	44.00	30.00	25.60	28.94
21	30	3.014908	101.648769	*Endospermum d.*	54.00	55.00	18.00	23.00	24.57
	31	3.014883	101.648729	*Streblus elongatus*	20.00	20.00	13.00	13.00	13.37
	41	3.014925	101.648747	*Streblus elongatus*	36.00	36.00	14.00	22.00	22.63
	48	3.015002	101.648715	*Burseraceae*	50.00	46.00	22.00	28.00	28.84
	49	3.01502	101.648684	*Streblus elongatus*	33.00	34.00	17.00	20.00	21.75
	50	3.014961	101.648652	*Hopea sulcata*	25.00	24.00	18.00	20.00	22.17
	51	3.014912	101.648648	*Macaranga spp.*	23.00	22.10	17.00	22.00	23.63
	52	3.014874	101.648636	*Myrysticaceae*	12.00	11.90	13.00	13.80	15.92
	60	3.014867	101.648734	*Pouteria malaccensis*	30.00	31.00	14.00	19.00	19.23
	63	3.014839	101.648761	*Hopea sulcata*	16.00	16.00	13.00	13.00	15.61
	71	3.014855	101.648779	*Artocarpus spp.*	39.00	39.70	14.00	15.00	16.45
	74	3.014913	101.648824	*Hopea sulcata*	28.00	28.20	18.00	18.20	18.44
22	5	3.027877	101.644552	*Dipterocarpus c.*	40.00	39.50	32.00	29.70	33.50
	15	3.027917	101.644522	*Shorea accuminata*	50.00	50.50	22.00	27.00	27.69
	17	3.027848	101.644486	*Dipterocarpus c.*	25.00	24.80	15.00	22.00	21.85
	22	3.027778	101.644515	*Artocarpus s.*	23.00	21.00	15.00	20.00	20.78
	26	3.027781	101.644566	*Hopea sulcata*	20.00	20.20	17.00	22.60	23.99
	27	3.027764	101.64466	*Hopea sulcata*	20.00	19.80	21.00	23.10	23.16
	28	3.027773	101.644605	*Dipterocarpus c.*	46.00	40.00	30.00	29.50	36.86
	29	3.02781	101.644594	*Hopea sulcata*	21.00	21.50	24.00	25.00	25.12
	31	3.027829	101.644682	*Shorea parvifolia*	21.00	21.00	21.00	19.90	25.70
	33	3.027863	101.644675	*Artocarpus nitidus*	24.00	21.10	21.00	17.00	20.87
	35	3.027897	101.644673	*Streblus elongatus*	27.00	27.00	14.00	16.30	18.65
	37	3.027867	101.644568	*Naphelium spp.*	47.00	48.00	32.00	29.00	32.94
	42	3.027943	101.644593	*Sandoricum koetjape*	24.00	24.50	16.00	20.50	24.55
23	1	3.028625	101.645231	*Dipterocarpus c.*	29.00	29.90	22.00	27.80	27.91
	2	3.02863	101.645312	*Dipterocarpus c.*	36.00	35.30	25.00	33.17	33.80
	3	3.028647	101.645319	*Dipterocarpus c.*	53.00	53.70	28.00	37.57	35.31
	4	3.028639	101.645251	*Dipterocarpus c.*	16.00	15.50	17.00	20.34	21.21
	8	3.028611	101.645277	*Shorea macroptera*	19.00	18.40	15.00	24.00	24.78
	9	3.028601	101.645269	*Palaquim gutta*	15.00	15.00	17.00	18.34	19.82
	11	3.028603	101.645217	*Gluta spp*	19.00	19.00	16.00	22.34	22.85
	13	3.028665	101.645136	*Canarium littorale f. r.*	35.00	34.90	24.00	26.17	31.45
	15	3.028585	101.64526	*Draceanaceae*	12.00	13.20	6.00	11.10	11.52
	16	3.028592	101.645321	*Pouteria m.*	25.00	26.10	19.00	24.81	25.75
	17	3.028555	101.645244	*Pentace spp.*	25.00	25.60	16.00	22.54	22.71
	18	3.028623	101.645331	*Dipterocarpus c.*	37.00	37.20	26.00	33.12	33.10
	23	3.028566	101.645189	*Dipterocarpus c.*	17.00	17.70	18.00	22.82	22.62
24	35	3.022029	101.646914	*Syzygium spp.*	30.00	29.30	15.00	15.40	18.31
	37	3.02197	101.646853	*Carallia brachiata*	10.00	10.30	10.00	13.90	15.67
	38	3.02195	101.646844	*Shorea m.*	39.00	35.30	20.00	25.30	27.36
	39	3.022016	101.646911	*Palaquim gutta*	22.00	23.00	17.00	19.70	19.79
	40	3.021982	101.646832	*Gynotroches a.*	39.00	40.80	14.00	21.30	21.10
	47	3.022102	101.646855	*Dialium spp.*	34.00	32.20	19.00	20.60	21.01
	56	3.022111	101.646981	*Herittiera spp.*	35.00	33.70	21.00	20.50	20.78

	57	3.02209	101.646991	*Shorea a.*	47.00	44.00	24.00	23.40	24.16
	58	3.022082	101.646961	*Streblus e.*	38.00	37.00	16.00	17.80	19.07
	59	3.022037	101.646997	*Metadina t.*	71.00	75.00	17.00	20.40	21.08
	61	3.022008	101.647018	*Lithocarpus spp.*	39.00	39.90	19.00	22.00	31.32
25	5	3.02231	101.64595	*Memecylon spp.*	19.00	19.00	15.00	20.00	21.52
	6	3.022338	101.645903	*Dipterocarpus c.*	35.00	32.20	18.00	26.60	26.39
	8	3.02239	101.645897	*Dipterocarpus c.*	15.00	14.80	14.00	23.40	23.91
	9	3.022374	101.645942	*Pentaspadon spp.*	19.00	18.90	14.00	17.20	18.30
	11	3.022392	101.645969	*Xylopia f.*	25.00	24.30	16.00	25.40	27.89
	13	3.022399	101.645945	*Artocarpus spp.*	10.00	10.00	11.00	12.00	14.65
	16	3.02242	101.645898	*Burseraceae*	11.00	10.40	10.00	13.00	13.31
	17	3.022423	101.645944	*Shorea a.*	42.00	41.20	8.00	23.00	22.77
	18	3.022383	101.64601	*Diospyros spp.*	39.00	39.10	13.00	25.40	28.49
	20	3.022446	101.646063	*Pellacalyx spp.*	17.00	16.90	18.00	19.90	20.89
	25	3.022409	101.646019	*Dipterocarpus v.*	72.00	73.20	26.00	38.00	38.06
26	2	3.021229	101.645088	*Mesua spp*	16.00	15.40	12.00	18.50	18.70
	4	3.021255	101.645136	*Rotoxylum spp.*	36.00	35.00	19.00	19.70	20.01
	5	3.021262	101.64509	*Shorea m.*	57.00	56.50	21.00	25.90	26.69
	9	3.021288	101.645194	*Syzygium spp.*	11.00	11.10	7.00	11.00	15.82
	10	3.021282	101.645135	*Naphelium spp.*	22.00	22.30	11.00	14.80	16.86
	13	3.021256	101.645179	*Artocarpus spp.*	27.00	27.00	18.00	24.60	26.02
	14	3.021186	101.64516	*Xylopia f.*	15.00	15.10	15.00	20.00	21.77
	19	3.021154	101.645157	*Ptenandra spp.*	11.00	11.00	9.00	12.80	15.19
	21	3.021246	101.645072	*Burseracea*	18.00	17.30	14.00	19.80	19.65
	23	3.021251	101.644972	*Lithocarpus spp.*	24.00	23.20	14.00	11.00	17.61
	24	3.021253	101.645025	*Myrysticaceae*	22.00	21.90	12.00	20.40	33.73

Appendix 7: Field photographs