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Forest Structure Measurement in Tropical Rainforest using Laser Scanning Technology

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Abstract – Numerous measurements can be made to extract the forest structure. Forest structure is one of the main aspects of forest management. The precise estimation of forest structure is vital for some forestry applications. Thus, this study presents a novel non-destructive approach for the measurement of forest structure using laser scanning technologies of airborne LiDAR and Terrestrial Laser Scanning (TLS). The study area was located at the forest campus of the Forest Research Institute of Malaysia (FRIM), Kepong, Selangor. The elements of forest structure that were measured: were canopy height; plant density and basal area. The field survey was conducted over 3 plots of 25 m radius circular shape with a total of 60 trees with diameter at breast height (DBH) of 10 cm and above. The tree canopy height was estimated based on canopy height model (CHM) of LiDAR data. For plant density, it was estimated based on crown delineation created from CHM. While, for TLS data, the extraction of individual trees was done using Cyclone algorithm. The forest structure measurement obtained from laser scanning technologies is proven to be reliable with the root mean square error (RMSE) of 5.415, *t*-test of 3.011, and *p*-value of 0.004 for canopy height. For basal area, the mean of RMSE, *t*-test and *p*-value was 0.22589, 0.620 and 0.324 for the overall 3 plots, respectively. The result obtained for plant density was one tree per meter^2. The final outputs were presented as the map of CHM, plant density and basal area map. In conclusion, laser scanning measurement improves and provides a precise technique for forest structure measurement.

Keywords – *Forest structure, Laser scanning, Tropical rainforest*

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1.0 Introduction

The forest can be defined as an ecosystem or assemblage of ecosystems that majorly included trees and other woody vegetation [1]. A forest has a different vertical structure as there are various layers of plants that can be recognized from the ground to the top of the tree. Each of these layers is usually composed of one or more dominant types of plants. There are many types of forests in the world such as tropical rainforests, Mediterranean forests, temperate forests, coniferous forests, and others. Each type of forest has different characteristics and behavior that is also known as forest structure such as basal area, biomass and others. In tropical forests such as Malaysia, the forest is usually very dense and full of diverse plants such as trees, shrubs, vines and epiphytes. Moreover, each forest type has a different forest structure in terms of its species, diversity, population structure, biodiversity and others [2].

The structure is a basic term that refers to the patterns and relationships between the elements within a well-defined system. The characteristics of a forest ecosystem, including biomass production, biodiversity and quality of ecosystem services, can be best determined with a large scope for its structure. For the forest structure, it can be defined as the conditions that describe the way of trees are being distributed in the forest [3]. For diversity, it can be related to specific forest structures in some aspects of heterogeneity or richness. Many elements can be reflected in the structure of the forest based on a variety of attributes [4]. The attributes of aboveground biomass, abundance, basal area, canopy height and plant density can be referred to define the particular forest structure. Each of the elements needs to be combined so that standard structure can be determined.

Forest structure is one of the main aspects of forest management. The spatial distribution of certain tree types is demanded to be analyzed by landscape ecology researchers [3]. The distribution of elements that fall inside or outside of forest land is more interesting rather than measuring the single trees. As for that, structure and diversity are the important features that can characterize a forest ecosystem. In addition, the knowledge of forest structure and diversity is necessary to study forest dynamics, plant-animal interactions and nutrient cycling [5]. However, there are more difficult in describing complex spatial structures than simple ones based on frequency distributions.

It is worthless to simply add together the various measures and produce some average quantification of forest structure [4]. Three main attributes of forest structure were extracted in this research. Those three attributes were canopy height, plant density and basal area. The first element was canopy height, usually used to describe the average height of the top of the tree canopy. The second element was plant density usually defined as the amount of space left between plants when planting a garden, field or other landscaping plants. The last element was a basal area referred to as the common term used to describe the average amount of an area (usually an acre) occupied by tree stems. All of the tree elements were chosen because of their major roles in presenting the relationship and pattern between trees in the forest that also reflected the forest structure [3, 27].

The canopy height of the tree is an important element that can show the competition between the trees in the forest to get sunlight and energy sources. Therefore, the relationship between the trees can be determined as the competition to get sunlight between them was identified [6]. Forest canopy height showed the highest vegetation components above ground level, which is essential in normalizing micrometeorological parameters and in estimating forest biomass and carbon pools. However, previous definitions of forest canopy height from inventory data bear uncertainties owing to arbitrary criteria of tall trees accounting for top height [6].

Subsequently, plant density is very important as it can be used for describing how much a site is being used and the intensity of competition between trees for the site’s resources [7]. Thus, the pattern and relationship between the distributions of the trees in the forest can be presented as the characteristics of the site or forest were determined. Besides, plant density is an important agronomic factor that manipulates the microenvironment of the field and affects the growth, development and yield formation of crops [8].

As for the basal area, it is used to determine more than just forest stand density; it is also linked with timber stand volume and growth. By referring to the timber stand volume and growth, the distribution way of the trees in the forest can be presented. Moreover, the basal area is often the basis for making important forest management decisions such as estimating forest regeneration needs and wildlife habitat requirements. [9]. By combining all three elements of canopy height, plant density and basal area, the overall forest structure can be extracted that shows the overall relationship and pattern of the trees in the forest.

The precise estimation of forest structure is vital for some applications including ecological modeling and carbon budget. Light detection and ranging (LiDAR) measure the three-dimensional structure of vegetation utilizing laser beams. Most LiDAR applications today depend on airborne platforms for data acquisitions, which commonly record between 1 and 5 "discrete" returns for each laser pulse. While airborne LiDAR permits examining of covering attributes at stand and forest level scales, there is a problem as largely insensitive to below canopy biomass such as understory and trunk volumes as these elements are often blocked by the upper parts of the crown, especially in denser canopies [28]. As a complement to airborne LiDAR, various previous studies utilized terrestrial laser scanning (TLS) for forest structure quantification in spatially restricted regions. Many TLS instruments can configure a fully digitize of the returned energy of an emitted laser pulse to establish a complete profile of the observed vegetation elements [10].

Furthermore, the limitations of airborne LiDAR are usually related to the capacity of the system to detect individual canopy elements. The factors of spatial density of the laser returns, size of the LiDAR footprint, scan angle and instrument power are affecting the LiDAR capability. As for that, airborne instruments are often unsuccessful in observing important aspects of the lower canopy and stem structure when these elements are blocked by the upper canopy [10]. Moreover, the data collected from airborne LiDAR is less suitable for describing the woody component of vegetation because the vertical projection of the stems contains only a little information about their shape and volume. These woody components, however, may contain a significant proportion of a stand's biomass.

In addition, quantitative forest estimations have generally been recorded utilizing manual ground-based survey procedures [11]. Whilst estimations, for example, tree diameter and height had been done effectively by utilizing this system, it is more challenging to acquire exact estimations of parameters, for example, tree taper without really felling the tree. Similarly, manual estimations are inclined to some level of estimation error. Therefore, the use of terrestrial laser scanning in producing quantitative forest parameters at the plot level can be implemented. Based on the previous research, it is suggested that the determination of the forest parameters such as tree diameter, taper and tree height can be measured directly from the laser scan point cloud return [11, 29].

There is study that reported that many previous studies have used ground-based or terrestrial LiDAR systems (TLS) as the accompaniment to airborne measurements, which can be used for describing canopy structure in a bottom-up rather than a top-down approach [10]. There are some fundamental dissimilarities in the way LiDAR and TLS can measure the distribution of foliage elements within a canopy. Firstly, the objects that are closer to the instrument have more capability in producing a measurable return. Therefore, LiDAR is probable to collect more detailed information about the upper canopy, while TLS is expected to provide a more detailed evaluation of the lower canopy. Thus, the integration of LiDAR and TLS can be very useful in determining the forest structure of a dense forest as both of them will fulfill the requirement of upper and lower canopy assessments [30].

This study aims to map the forest structure by using laser scanning technology data. The aim is supported by the following specific objectives:

i. To generate Canopy Height Model (CHM) from airborne LiDAR data.
ii. To produce individual tree crown delineation and estimate plant density using LiDAR data.
iii. To calculate the basal area using DBH extracted from Terrestrial Laser Scanning.

2.0 Materials and Method

The methodology is divided into four phases namely data collection, data pre-processing, data processing and result and analysis (Figure 1). The first phase is focusing on collecting terrestrial laser scanning (TLS) data and field data. While the LiDAR data that was acquired in 2013 has been used as primary data. The second phase generally involves the pre-processing procedure of both LiDAR and TLS data. For LiDAR data, it will undergo the process of filtering the point clouds to the ground points. Meanwhile, for TLS data, the registration of the point clouds generated from different scan stations, noise removal and extraction of the individual trees will be done in this stage. A noise removal process is required to clean the point clouds of individual trees from understory vegetation and neighboring trees that are not needed and could lead to misinterpretation of the single tree.

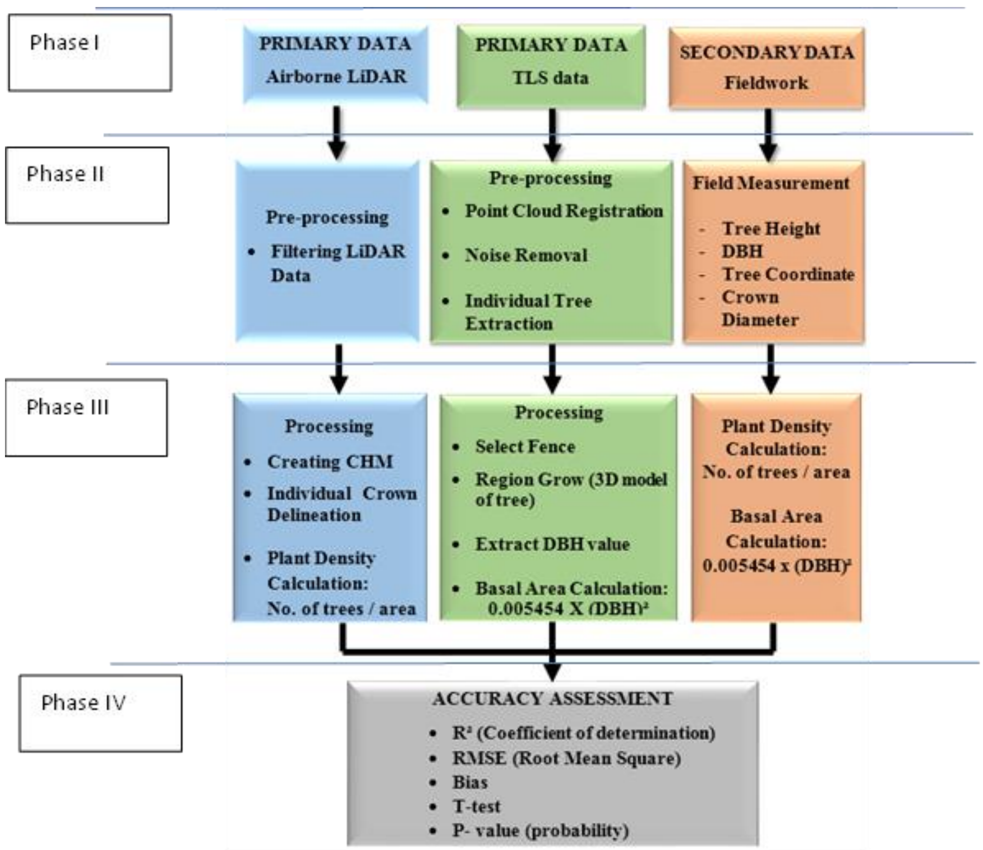

Figure 1. Flow chart of the research

The third phase is majorly devoted to extracting the attributes of the forest structure. In this stage, for LiDAR data, the canopy height model (CHM) will be generated and the individual tree crown delineation will be produced for estimating the plant density. Meanwhile, for TLS data, the 3D model of the trunk will be generated by using a fence and region growing tool for extracting the diameter at breast height (DBH) of each tree and next the basal area calculation was conducted. The fourth phase is the assessment of results using root mean square error (RMSE), correlation of determination, mean bias, t-test and probability value.

2.1 Study Area

The study area of this research is in Lagong Hill Forest Reserve, forest campus, FRIM that has been gazetted as a reserve forest. The forest is located in Kepong, Selangor that was approximately 20 kilometers away from the Kuala Lumpur city. It has a total area of 3624.1 hectares that is surrounded by a planted forest where the trees are being replanted. Moreover, Lagong Hill Forest has an altitude of 290 meters up to approximately 575 meters at the peak. The area is a humid area that has an average daily temperature of 27ºC to 32 ºC. It has abundant rainfall of 2000 to 2900 mm. Various species of trees can be found in this forest such as Dipterocarpus Baudii, Strombosia Javanica, Litsea, Dryobalanops Aromatica and others. Lagong Hill Forest Reserve also surrounding by Dipterocarp trees that can grow very tall and large in a long time. The trees in this forest have a height between 25 m to 45 m for certain species. The reason for selecting the Lagong Hill Forest, FRIM as the study area is because of it can represent the tropical forest characteristic very well which is needed in this research.

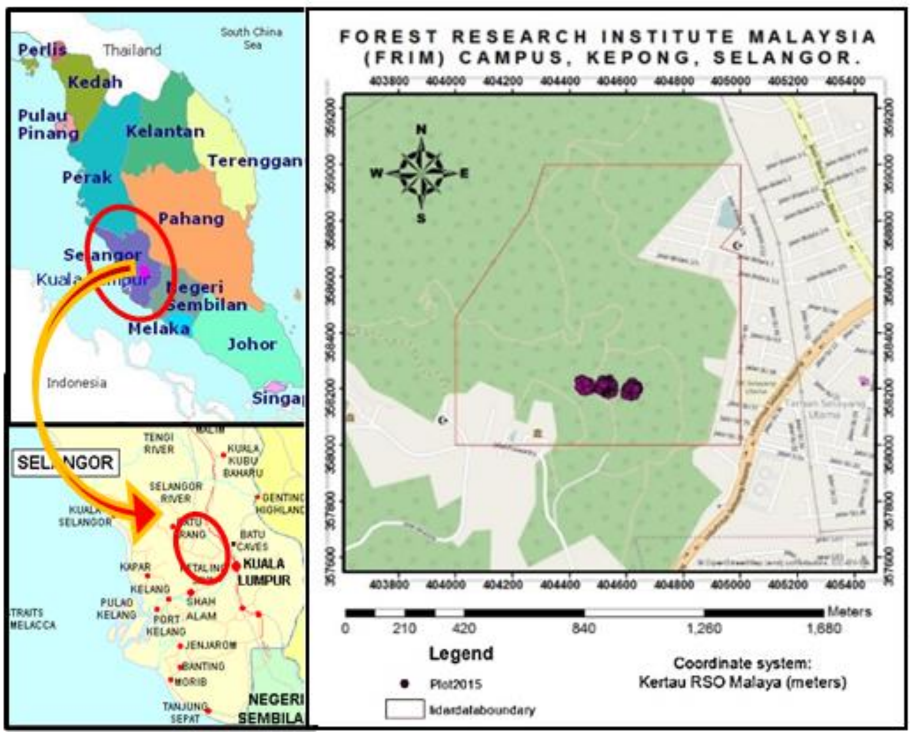

Figure 2. Study area in Forest Campus, FRIM

2.2 Data Collection

The field data collection of individual tree measurement involved two different approaches which are a conventional method and terrestrial laser scanning. Both measurements are carried out in the same study area that included three forest plots of 25 m radius circular shape (see Figure 3). However, before the process of scanning, the process of marking a single tree must be done by marking the tree with a unique number and tree measurement such as the location of trees, diameter at breast height (DBH), tree species, tree height (whenever possible) and crown base height are recorded in a special form. The tree measurements are made for only the trees that had a diameter at breast height (DBH) of 10 centimeters and above. The locations of trees were measured using total station (TS) with local coordinate reference observed by static GPS in the open area. Table 1 shows the list coordinate of center plot (CP) and scan Stations (SC) of TLS in the RSO (Rectified Skew Orthomorphic) Coordinate System.

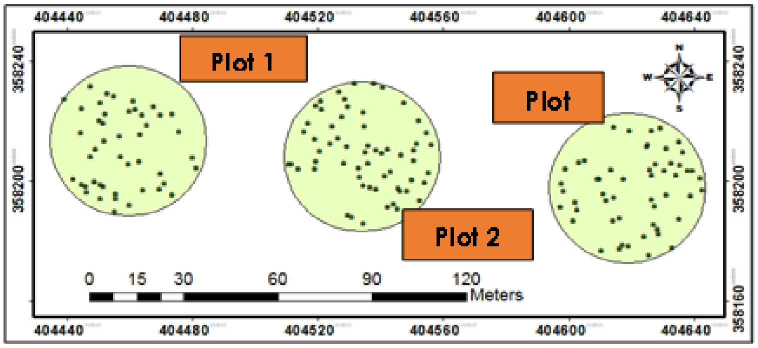

Figure 3. Location of Plot 1, Plot 2 and Plot 3

Table 1. Coordinate of Center Plot (CP) and Scan Stations (SC) of TLS in RSO Coordinate System

Location	Plot 1 (E,N)	Plot 2 (E,N)	Plot 3 (E,N)
CP/SC1	404459.37,358213.38	404533.93,358208.12	404618.72,358197.76
SC 2	404457.22,404457.22	358226.23,404531.33	404635.24,358195.33
SC 3	404442.93,358220.68	404512.65,358204.10	404616.40,358218.91
SC 4	404457.95,358192.60	404532.92,358187.86	404599.77,358198.82
SC 5	404479.98,358213.10	404561.25,358212.57	404611.83,358182.84

Detailed measurement of individual trees was assisted by a terrestrial laser scanner (TLS) and LiDAR data. As for that, all three plots will be scanned by the TLS with 5 scanning positions which include one position in the center and four positions at the edge of a plot (Figure 4). The data will be collected by using Terrestrial Laser Scanner Leica C10 ("All-in-one laser scanner") (Table 2) which is used for acquiring highly detailed and accurate data.

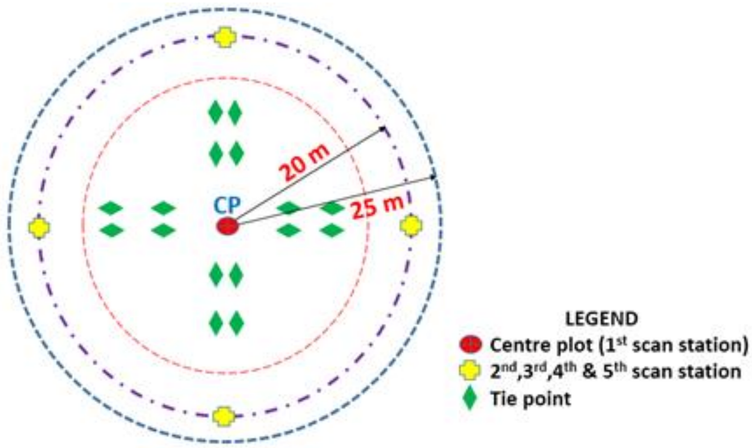

Figure 4. Laser scanning configuration for a forest plot

Table 2. Leica C10 ("All-in-one laser scanner") specification

Type	Specification
Wavelength	Green; 532nm (visible)
Scan Rate	Up to 50,000 points/sec
Field Of View	360° on horizontal axis; 270° on vertical axis
Accuracy	Position: 6mm; Distance: 4mm; Modelled surface precision/noise: 2mm; Target acquisition: 2mm std. deviation

LiDAR data had been collected in the year of 2013. This data was acquired from AAM Pty Limited. The data is a high-density discrete pulse-based backscattered LiDAR with 8.6-point density that covered 89 hectares of area. The details about the airborne LiDAR data are shown in Table 3.

Table 3. Specification of LiDAR data

Type	Specification
Ground points	93287
Never classified points	737606
Intensity	1038
Point Density	8.5999 per m²
Point Spacing	0.341

2.3 Data Pre-Processing

For LiDAR data, the pre-processing phase will be involved the process of filtering the point cloud into the ground point. In this study, the software used is ALDPAT which is an open source. In this software, there are many different algorithms provided. However, the algorithm used in this study was the Adaptive TIN (ATIN) Filter which uses the distance of a point on the surface of a TIN to select ground points from LiDAR data sets. This filter will select a few low points that are most likely a terrain surface that further will be triangulated to produce TIN. The main strength of this algorithm lies in its ability to handle surfaces with discontinuities, which is a particularly useful characteristic in urban areas [12].

Meanwhile, for TLS data, the pre-processing phase included the process of registration where each scanning position will be registered into the local coordinate system. Using TLS for generating the point clouds of trees in forest areas requires multiple scanning processes such as wise selection of scanning positions. This is a very crucial aspect in ensuring the production of detailed and dense point clouds for individual trees. Each point cloud produced at a different scanning position will be combined and registered using common tie points located in the selected points in each forest plot. The highly reflective tie points were located randomly in the field and should be seen by all scanning positions. The point clouds will be transferred to the local ground coordinate system by using the real coordinate measurement produced by TS and GPS.

After that, the registered point clouds of TLS will undergo the process of removing noise for individual tree delineation. The noise removal process involves clearing and deleting the unwanted point cloud from the targeted individual tree to avoid confusion and complexity in the data processing. The noises that need to be removed such as bushes, understory trees, neighbouring trees and ground surface. Subsequently, the individual tree extraction is done where we can see a clear view of the point clouds that represent an individual tree. Therefore, the process of extracting diameter at breast height (DBH) can proceed in the next step.

2.4 Estimation of Canopy Height Model (CHM) using LiDAR

The Canopy Height Model (CHM) was generated through the subtraction of the Digital Terrain Model (DTM) from the Digital Surface Model (DSM) also a digital representation of height [13]. Moreover, the creation of an accurate DTM is the first step in extracting reliable canopy heights from LiDAR data. This is very crucial as the accuracy of deriving the ground elevation can directly affect the accuracy of measuring tree heights [14]. Therefore, by using the filtered LiDAR data of pre-processing results the creation of DTM and DSM can be made. Later, by subtracting the DSM from DTM, the output of CHM will be produced as shown in equation 1.

$$CHM = DSM - DTM \quad (1)$$

Where:

CHM = Canopy Height Model;

DSM = Digital Surface Model; and

DTM = Digital Terrain Model.

2.5 Individual Tree Crown Delineation using LiDAR Data

The CHM will be used for creating the individual tree crown delineation that represents the crown of every single tree in the forest and the number of trees or tree counting process can be made. There are many different algorithms that had been introduced for delineating an individual tree crown. For this study, the algorithm used is the "inverse watershed segmentation algorithm" which has the capability in achieving high accuracy and fast computing of tree crown delineation. Furthermore, this algorithm involved three important steps (Figure 5). The final output will be the individual crown for each tree that shows the boundary between one tree crown and another. Thus, that individual tree crown can be used for indicating the number of trees per forest that is required in measuring the plant density of the forest.

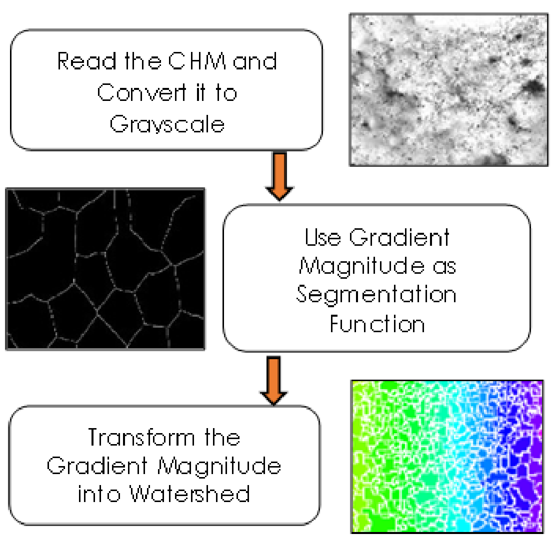

Figure 5. Steps of Inverse Watershed Segmentation using CHM

2.6 Measurement of Plant Density

"Density" in plant ecology is defined as the number of individuals of a given species that occur within a given sample unit or study area [15]. Density is often used in a vegetation survey to describe a species' status in a plant community. Yet, there are several problems that could occur in obtaining an estimate of density. Included are the definition of an individual plant, the size and shape of a sampling unit with associated boundary errors for inclusion of a plant within the plot area, and the use of estimates from variable area plots. In this study, the number of trees is obtained through the process of crown delineation of CHM and the overall procedure is shown in Figure 6 below.

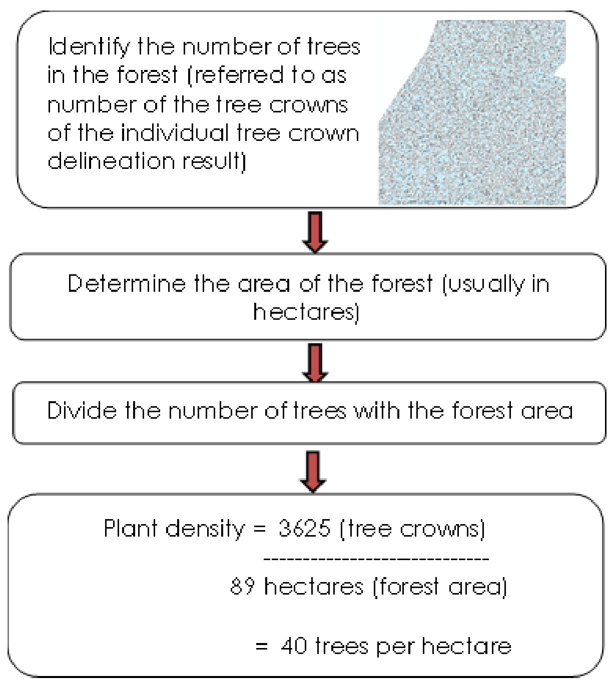

Figure 6. Procedures of Plant Density Estimation

The measurement of plant density is generated by dividing the number of trees by the unit area of the forest with the output of trees per hectare as shown in equation (2).

$$\text{Plant density (tree per hectare)} = \frac{\text{Number of tree}}{\text{Area}} \quad (2)$$

Where:

Number of tree = Number of trees in forest; and

Area = Area of forest (in hectare)

This plant density is very important as it can be used for describing how much a site is being used and the intensity of competition between trees for the site's resources [7].

2.7 Extraction of Diameter at breast height (DBH) using TLS Data

Diameter at breast height is referred to the diameter of a tree stem measured at breast level as a convenient way of measurement during which one does not need to bend his waist or climb up a ladder to take the measurement. For a more precise measurement, there is a need to standardize the "breast height". In the United States, DBH is measured at a height of 4.5 feet (1.3 meters) above ground [16]. In this study, the DBH values are extracted from the TLS point cloud by using the Cyclone algorithm that had the capability in providing point cloud users with the widest set of work process options for 3D laser scanning projects in engineering, surveying, construction and related applications.

Figure 7 shows the overall procedure of DBH extraction using TLS data based on the result of individual trees extracted before, a further step of extracting DBH is proceeded. By using the Fencing method, select the tree stem at breast height (1.3 meters) and 3D model of the selected tree stem is generated using the Region Grow method. For the Region Grow method, there are two different shape selections of cylinder and sphere. In this study, the shape used is cylinder as the tree stem is in the cylinder shape so that the diameter of that particular tree stem can be extracted from that 3D model that will be referred to as a DBH.

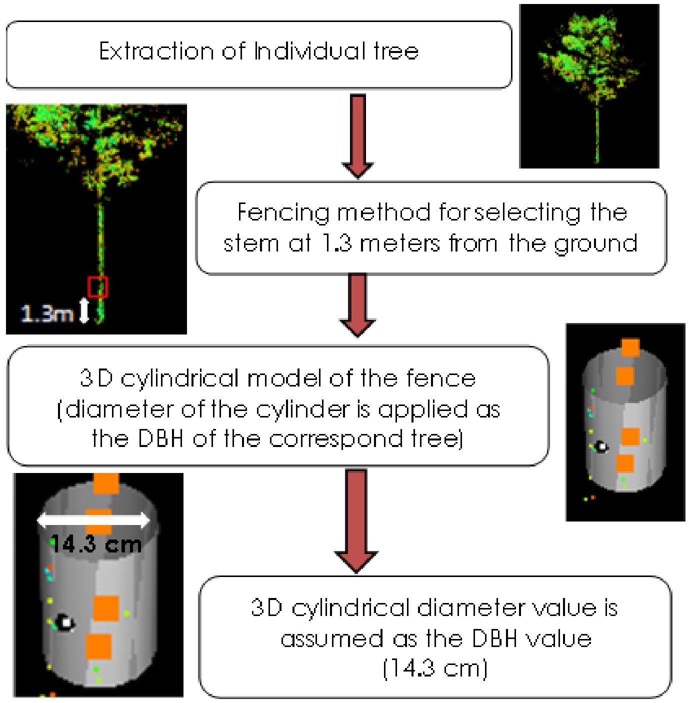

Figure 7. DBH Extraction Process

2.8 Calculation of Basal Area

Basal area is the common term used to describe the average amount of an area (usually an acre) occupied by tree stems. It is defined as the total cross-sectional area of an individual tree in a stand measured at breast height, and expressed as per unit of land area (typically square feet per acre) [9]. Before, the usage of stem density and DBH were being implemented in calculating basal area [17]. However, as the trees grow, the stem density becomes meaningless, especially in estimating the timber volume and it is sufficient for a diameter of trees at DBH to determine how many trees per acre it takes to make a given basal area [17]. The basal area can be calculated by using equation (3) as shown below:

Per tree:

$$\text{Basal area per tree (square feet)} = 0.005454 \times (DBH)^2 \tag{3}$$

Where:

0.005454 = "foresters constant", which converts inches into square feet; and

DBH = Diameter at Breast Height.

2.9 Accuracy assessment

Assessment is a compulsory procedure in order to determine the accuracy of the estimated canopy height, plant density and basal area by using a remote sensing approach of laser scanning technology for the whole study area. For canopy height and basal area calculation, the difference of results derived using laser scanning technologies are being compared with the field data and analysed with RMSE, BIAS, t-test and probability value. In addition, a correlation of determination (R^2) was made to show the dependency of data between results obtained from laser scanning technologies with the field data.

Root Mean Square Error (RMSE) (also known as Root Mean Square Deviation) is one of the most widely used statistics in GIS. RMSE can be used for a variety of geostatistical applications. RMSE measures how much error there is between two datasets (see equation (4)). RMSE usually compares a predicted value and an observed value.

$$\text{RMSE} \quad \sqrt{\frac{1}{n}\sum_{i=1}^{n}(e_i - m_i)^2} \tag{4}$$

Where:

e = estimated value;

m = measured value; and

n = number of sample

In statistics, the bias (or bias function) of an estimator is the difference between this estimator's expected value and the true value of the parameter being estimated (see equation (5)). An estimator or decision rule with zero bias is called unbiased. Otherwise, the estimator is said to be biased. In statistics, "bias" is an objective statement about a function.

$$\text{BIAS} \quad \frac{1}{n}\sum_{i=1}^{n}(e_i - m_i) \tag{5}$$

Where:

e = estimated value;

m = measured value; and

n = number of samples

3.0 Results and Discussions

The results that were obtained in this study included the generation of the Canopy Height Model (CHM), plant density measurement, extraction of Diameter at Breast Height (DBH) and calculation of basal area.

3.1 Estimation of Canopy Height Model (CHM)

Canopy Height Model (CHM) can be generated by using LiDAR data as stated before. The overview of CHM is to display the variation of the height of the study area onto a map which can be used for further analysis as shown in the Figure 8. While, Table 4 refers to the description of tree height for a total of 60 trees from LiDAR and field measurement data in Plot 1, Plot 2 and Plot 3, respectively.

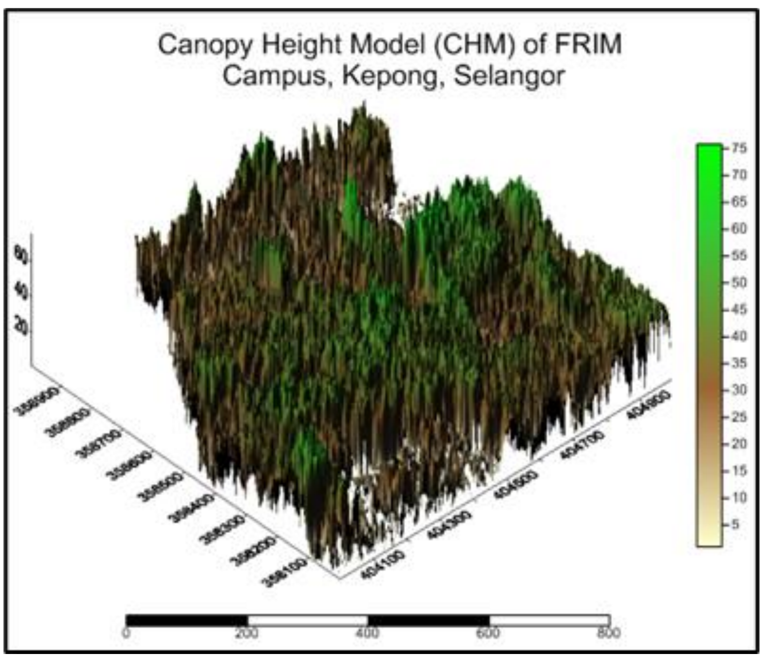

Figure 8. Map of Canopy Height Model (CHM) of FRIM Reserve Forest, Kepong

Table 4. Description of Tree Height for 60 trees

No.	Tree No.	Tree Height		No.	Tree No.	Tree Height		No.	Tree No.	Tree Height	
	Plot 1	LiDAR	Field Data		Plot 2	LiDAR	Field Data		Plot 3	LiDAR	Field Data
1	A01	28.799	34.000	21	B02	24.882	20.690	41	C01	23.979	23.442
2	A02	38.382	42.233	22	B03	24.973	20.450	42	C02	16.842	15.205
3	A03	29.423	32.302	23	B04	30.210	25.578	43	C03	27.775	26.000
4	A04	24.223	26.090	24	B05	34.401	29.204	44	C04	38.876	36.451
5	A05	36.141	37.000	25	B06	25.974	20.500	45	C05	24.733	21.842
6	A06	32.861	33.700	26	B07	38.317	32.740	46	C06	35.357	32.068
7	A07	20.667	21.390	27	B08	31.350	25.470	47	C07	28.921	25.008
8	A08	24.857	25.460	28	B09	27.264	21.320	48	C08	28.743	24.780
9	A09	32.741	33.000	29	B10	26.889	20.739	49	C09	39.563	35.573
10	A10	29.192	29.000	30	B11	37.208	30.216	50	C10	27.414	23.259
11	A11	23.979	23.442	31	B12	30.251	23.020	51	C11	24.882	20.690
12	A12	16.844	15.205	32	B13	32.387	24.620	52	C12	24.973	20.450
13	A13	27.775	26.000	33	B14	34.809	27.000	53	C13	30.210	25.578
14	A14	38.876	36.451	34	B15	33.248	25.334	54	C14	34.401	29.204
15	A15	24.733	21.842	35	B16	29.519	21.120	55	C15	25.974	20.500
16	A16	35.357	32.068	36	B17	29.210	20.730	56	C16	38.317	32.740
17	A17	28.921	25.008	37	B18	34.042	25.560	57	C17	31.350	25.470
18	A18	28.743	24.780	38	B19	25.977	17.360	58	C18	27.264	21.320
19	A19	39.563	35.573	39	B20	31.144	21.420	59	C19	26.889	20.739
20	A20	27.414	23.259	40	B02	30.545	20.667	60	C20	37.208	30.216

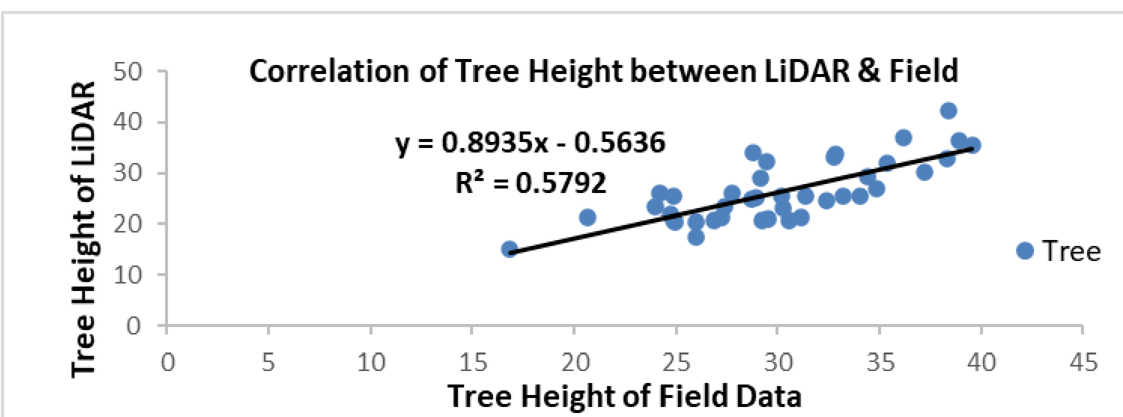

Figure 9. Correlation of Tree Height between LiDAR & Field Data

Table 5. *t*-test: Paired Two Sample for Means

	Variable 1	***Variable 2***
Mean	16.844716	15.2057
Variance	25.94685774	36.2208
Observations	60	60
Hypothesized Mean Difference	0	
df	59	
t Stat	3.01122	
P(T<=t) one-tail	0.001753	
t Critical one-tail	1.671093032	
P(T<=t) two-tail	0.003506	
t Critical two-tail	2.000995378	

Hypothesis:

H_0 : HLiDAR = HField / ρ = 0

H_1 : HLiDAR ≠ HField / ρ ≠

The *ρ*-value (0.004) is less than 0.05, H_0 is rejected, where there is sufficient evidence to conclude that the population correlation is not equal to 0.

Table 6. Statistical Analysis Result of Tree Height of Field and LiDAR Data

RMSE	**Mean Bias**	**R²**	***t*-test/df (*p*-value)**
5.415	3.764	0.579	3.011/59 (0.004)

The statistical analysis results as above (Table 6) show that the RMSE and correlation of determination (R^2) analysis give significant test results for the comparison of LiDAR tree height and field tree height (Figure 9 and Table 5). Based on Figure 9, it shows medium correlation between the tree heights of both methods with 57.9 per cent dependency of the tree height LiDAR with the tree height of the field. The RMSE and Mean Bias values are moderate that indicates the moderate difference between tree heights of both methods. The reason of this error happened is because of the possibility that the identified tree tops in the LiDAR were actually coming from LiDAR hits within the crown and not the true top of the tree [18]. Thus, the identified tree height is not the actual height that was supposedly directly measured from the tree's crown top. However, this also can be due to the mistake in field measurement as there are some cases in which the tree height is too high (more than 75 meters) that overlapped with the other trees as tropical rainforests had a very close gap between the trees and difficult to recognize the part of the crown that was directly over the base. Thus, it could lead to the misinterpretation of the tree height [19]. Therefore, based on the statistical analysis shows the capability and the use of LiDAR in measuring the forest structure parameters [20].

3.2 Measurement of Plant Density

Plant density is measured by dividing the number of trees in the forest by the forest area as stated before.

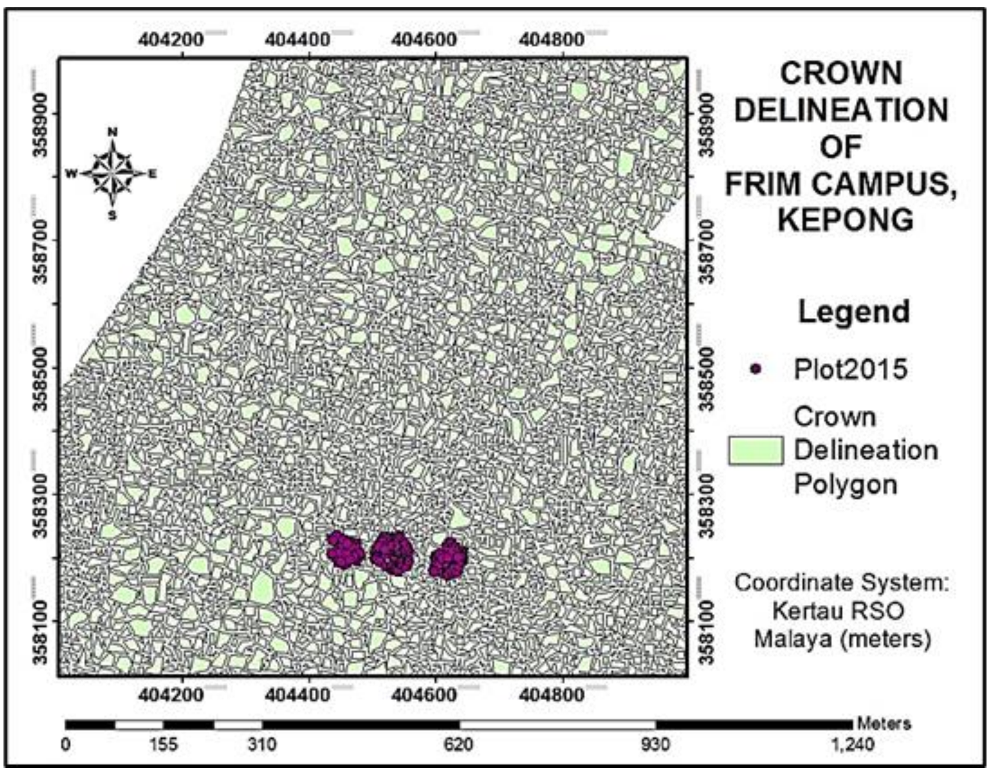

Figure 10. Map of Individual Tree Crown Delineation of FRIM Reserve Forest, Kepong

Figure 10 shows the overall result of individual tree crown delineation of LiDAR data that covers the FRIM Reserve Forest. The calculation of plant density of overall LiDAR data is made by dividing the total number of trees which is 3625 with the area of 89 hectares of the LiDAR data.

The result of plant density was 40 trees per hectare. The result of plant density is influenced by the generated tree crown delineation. The result of plant density estimation will be more significant if the result of the individual tree crown delineation is accurate for determining the number of trees in the forest [21]

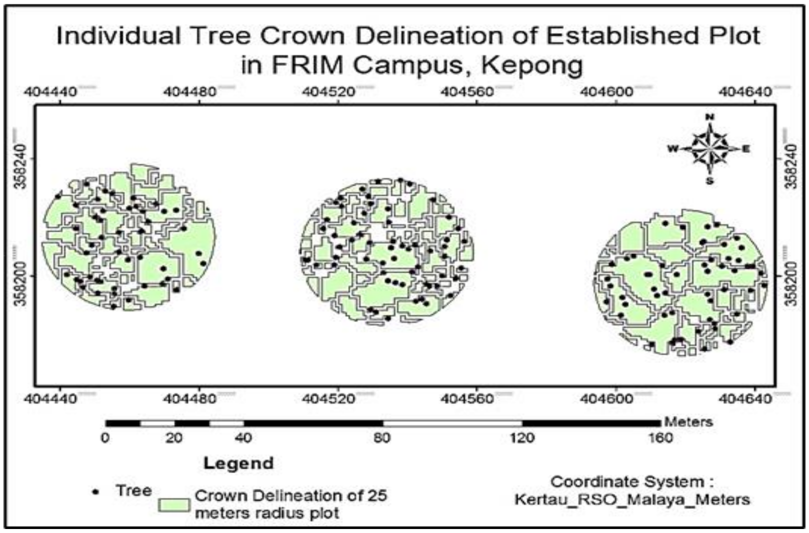

Figure 11. Map of Individual Tree Crown Delineation of Each Plot in FRIM Reserve Forest, Kepong

Figure 11 shows the result of individual tree crown delineation of CHM generated from LiDAR data for each plot. The tree crown for each individual trees are shown as the polygon that representing the boundary of their own crowns.

Table 7. Comparison of Plant Density between Field and LiDAR Data

Plot	(Field) No. Of Tree	(Field) Plant Density	(LiDAR) No of Tree	(LiDAR) Plant Density
1	46	1 tree per m^2	49	2 trees per m^2
2	60	2 trees per m^2	64	3 trees per m^2
3	53	2 trees per m^2	40	1 tree per m^2

Table 7 represents the comparison of plant density for each of the plots where it is not much difference between field and LiDAR plant density. The difference is only one tree per m^2 for each plot as the plant density is calculated based on the number of trees per area (m^2). This is partly due to canopy outspreading where the spacing between tree crowns is often less than 1 m which led to difficulty in differentiating the individual tree crown for each tree [22].

3.3 Extraction of Diameter at Breast Height (DBH) from TLS

Diameter at Breast Height (DBH) is obtained through the process of noise removal up to the single tree extraction. As the single tree is extracted, a 3D model of the tree stem will be produced and the value of its diameter can be obtained. Figures 12 and 13 show the result of pre-processing of the TLS data of removing noise and extracting individual tree.

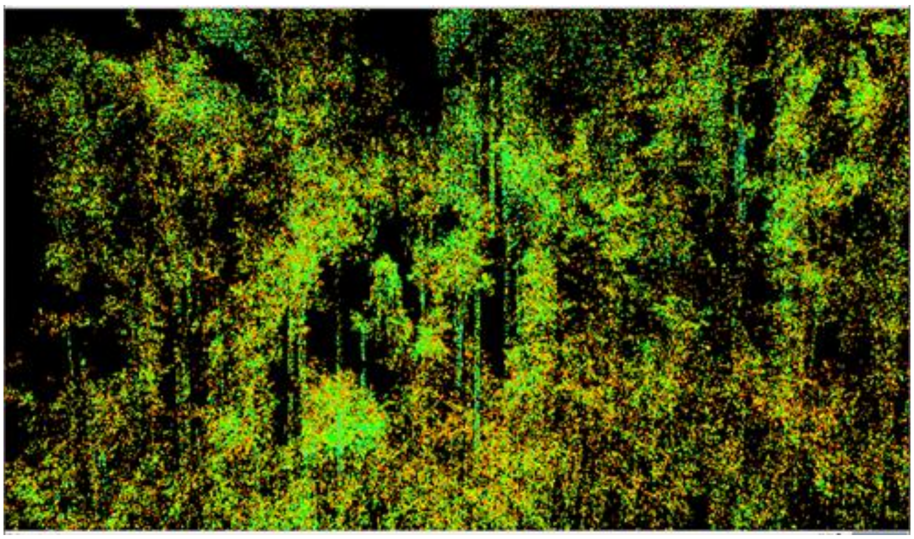

Figure 12. Noise Removal Result of TLS Data

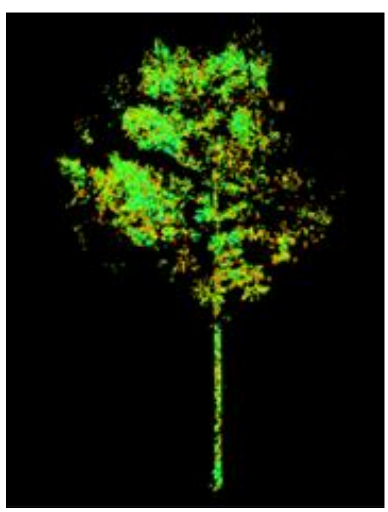

Figure 13. Individual Tree Extraction of TLS Data

Based on Figure 12, the result of removing the noise and all of the unwanted data that represent only the trees is basically done using the fencing technique that produced the limit area used in a rectangle and determined the area to be removed, either the inner or outer rectangle. To obtain a very quality of 3D modeling, the process of removing noise needs to be performed which finally produced an individual tree stands as in Figure 13 [23].

Figure 14 shows the 3D cylindrical model of the tree stem of an individual tree at 1.3 meters above the ground. The diameter value can be obtained from the object info properties of that cylindrical model. A similar procedure and result are obtained from all of the selected individual trees. The extraction process of DBH of TLS point cloud using Cyclone algorithm gave a very high accuracy as it is not much difference between the DBH extracted using Cyclone algorithms with the DBH measured in the field. Moreover, the capability of the Cyclone algorithm in fitting the cylinders that represented the tree stem also provides an optimum result of the DBH value of each individual tree [24]. Table 8 shows the description of DBH for 60 trees observed using TLS and field measurements data, respectively.

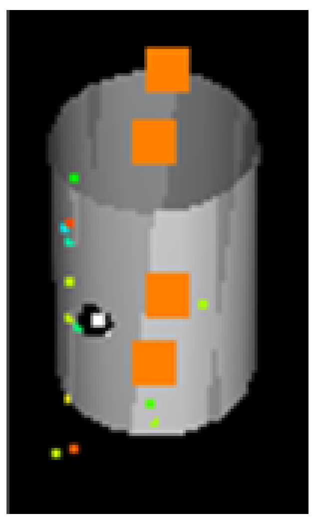

Figure 14. Cylindrical 3D Model of tree stem

Table 8. Description of DBH for 60 trees from TLS and field measurements data

No.	Tree No.	DBH		No.	Tree No.	DBH		No.	Tree No.	DBH	
	Plot 1	TLS	Field Data		Plot 2	TLS	Field Data		Plot 3	TLS	Field Data
1	A01	35.1	35.3	21	B02	18.3	19.1	41	C01	32.3	34.5
2	A02	47.8	47.0	22	B03	75.7	69.9	42	C02	55.9	52.2
3	A03	43.7	43.5	23	B04	70.9	71.1	43	C03	42.4	42.2
4	A04	37.2	38.3	24	B05	67.4	64.3	44	C04	36.1	38.4
5	A05	36.3	35.1	25	B06	34.8	33.4	45	C05	51.1	53.8
6	A06	99.6	99.6	26	B07	79.8	75.6	46	C06	47.8	48.4
7	A07	18.3	19.1	27	B08	32.4	33.9	47	C07	62.5	61.1
8	A08	40.1	39.7	28	B09	28.2	20.9	48	C08	58.4	56.9
9	A09	18.5	19.4	29	B10	54.2	56.1	49	C09	72.4	75
10	A10	59.2	61.6	30	B11	21.6	22.6	50	C10	74.9	74.8
11	A11	72.4	69.9	31	B12	22.9	19.1	51	C11	57.2	55.2
12	A12	55.4	61.8	32	B13	48.0	53.7	52	C12	34.3	34.1
13	A13	45.4	44.2	33	B14	56.0	52.6	53	C13	64.8	64.2
14	A14	29.5	28.6	34	B15	52.3	49.5	54	C14	27.4	28.5
15	A15	40.1	40.8	35	B16	38.9	34.1	55	C15	69.1	68.6
16	A16	41.7	40.3	36	B17	17.6	18.1	56	C16	100.1	99.5
17	A17	36.1	37.3	37	B18	60.2	62.6	57	C17	90.7	90.2
18	A18	73.4	72	38	B19	59.9	56.7	58	C18	82.0	80.5
19	A19	33.0	33.9	39	B20	58.2	57.7	59	C19	85.2	84.0
20	A20	27.4	23.3	40	B02	59.6	66.0	60	C20	112.5	111.2

3.4 Calculation of Basal Area

Basal area is calculated for each tree based on the formula stated before. The result of basal area estimation for FRIM Reserve Forest is shown as in the Figure 15. The result of basal area for overall 60 trees of the three plots is shown below (Table 9). The output of basal area is in the unit of square feet per acre.

Table 9. Description of Basal Area for all tree plots (60 trees)

No.	Tree No.	Basal Area		No.	Tree No.	Basal Area		No.	Tree No.	Basal Area	
	Plot 1	**TLS**	**Field Data**		**Plot 2**	**TLS**	**Field Data**		**Plot 3**	**TLS**	**Field Data**
1	A01	1.053	1.039	21	B02	0.308	0.283	41	C01	1.006	0.880
2	A02	1.867	1.928	22	B03	4.130	4.844	42	C02	2.304	2.640
3	A03	1.600	1.614	23	B04	4.274	4.250	43	C03	1.505	1.521
4	A04	1.240	1.169	24	B05	3.495	3.840	44	C04	1.247	1.100
5	A05	1.042	1.115	25	B06	0.943	1.024	45	C05	2.447	2.203
6	A06	8.386	8.381	26	B07	4.832	5.383	46	C06	1.980	1.928
7	A07	0.308	0.283	27	B08	0.972	0.887	47	C07	3.156	3.301
8	A08	1.332	1.362	28	B09	0.369	0.672	48	C08	2.737	2.885
9	A09	0.318	0.291	29	B10	2.661	2.483	49	C09	4.755	4.430
10	A10	3.208	2.959	30	B11	0.432	0.394	50	C10	4.730	4.746
11	A11	4.130	4.430	31	B12	0.308	0.443	51	C11	2.576	2.761
12	A12	3.229	2.592	32	B13	2.438	1.948	52	C12	0.983	0.994
13	A13	1.652	1.743	33	B14	2.339	2.651	53	C13	3.484	3.546
14	A14	0.691	0.734	34	B15	2.071	2.312	54	C14	0.687	0.636
15	A15	1.407	1.362	35	B16	0.983	1.279	55	C15	3.978	4.035
16	A16	1.373	1.467	36	B17	0.277	0.262	56	C16	8.369	8.467
17	A17	1.176	1.100	37	B18	3.313	3.064	57	C17	6.878	6.951
18	A18	4.382	4.555	38	B19	2.718	3.033	58	C18	5.478	5.690
19	A19	0.972	0.922	39	B20	2.814	2.863	59	C19	5.965	6.139
20	A20	2.348	2.433	40	B02	3.682	3.003	60	C20	10.453	10.703

The result of basal area estimation for FRIM Reserve Forest is shown as in the Figure 15 below:

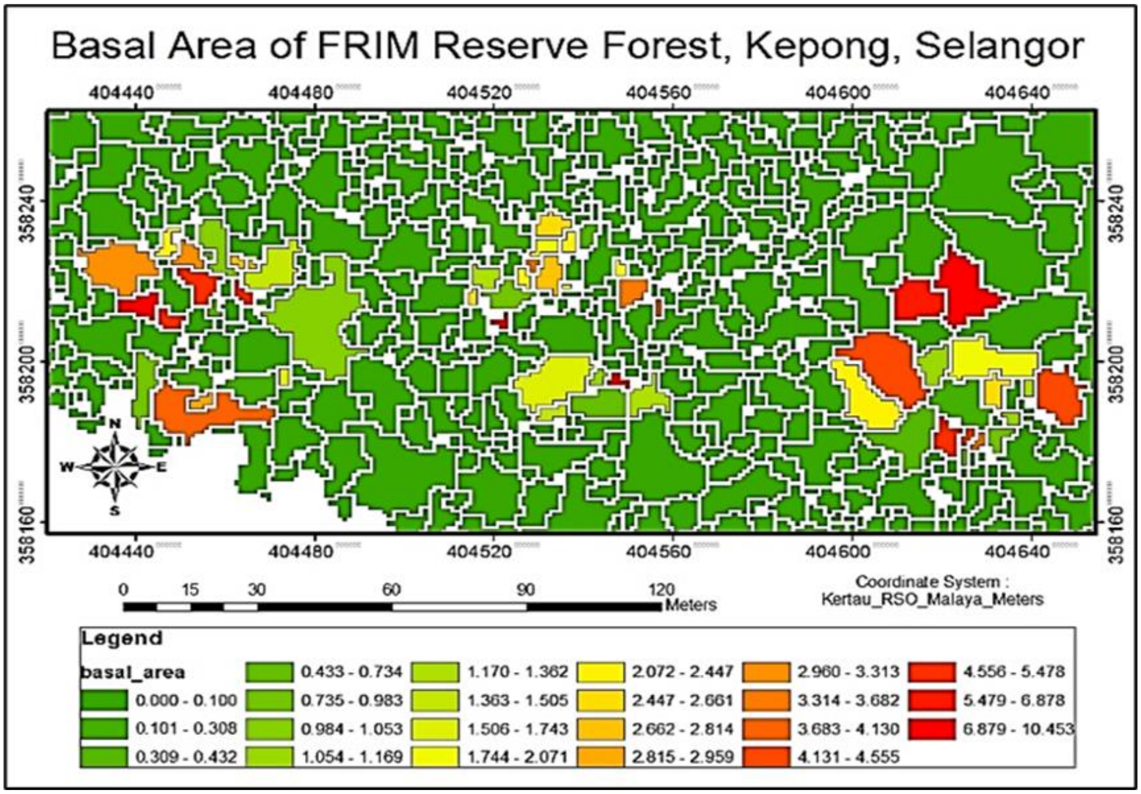

Figure 15. Basal Area of FRIM Reserve Forest, Kepong

While the statistical test of the Basal area of field data and TLS data are given in Table 10:

Table 10. Statistical Analysis Result of Basal Area of Field and TLS Data

Plot	RMSE	Mean Bias	R^2	*t*-test/df (*p*-value)
Plot 1	0.179	0.012	0.991	0.984/19 (0.393)
Plot 2	0.332	-0.078	0.956	0.873/19 (0.305)
Plot 3	0.167	-0.042	0.997	0.012/19 (0.273)

The statistical analysis results as above (Table 10) show that the RMSE and correlation of determination (R^2) analysis give significant test results for the comparison of TLS basal area and field basal area. For the correlation of determination (R^2), it shows a very height correlation between the basal area of both methods with more than 95 per cent dependency of the basal area

TLS with the basal area field for all three plots. The RMSE and Mean Bias values are very low which less than one. This indicates that there is not much difference between the basal area obtained of both methods. To get an accurate basal area, we first need to have a very good quality DBH as it is the only parameter used to calculate the basal area. Accurate DBH measurements could be derived if the TLS sensor's view is unobstructed by branches and other objects [25]. Furthermore, the forest application using TLS has also extended beyond traditional inventory parameters as TLS seems well-poised to address the limitations of traditional forest measurement. However, there are probably two main shortages of using TLS in forest applications as the forest usually has trees in dense stands that are sometimes partly shaded by other trees and branches could be confused with tree stems [26]. In this study, for overcoming the problems of branches and other obstructions, the process of removing those point clouds is done carefully to ensure only the selected point cloud of single tree stems can be obtained. Thus, the accurate DBH can be extracted based on that the single tree stems that also give the accurate basal area.

Basal area is a useful index for understanding forest-wildlife habitat relationships and making timber harvest decisions [9]. Subsequently, the basal area is used to determine more than just forest stand density; it is also linked with timber stand volume and growth. Therefore, it is often the basis for making important forest management decisions such as estimating forest regeneration needs and wildlife habitat requirements. The manipulation of stand basal area to achieve forest management goals can be as important as the use of prescribed fire or other vegetation treatments [9].

4.0 Conclusion

Airborne laser scanning technologies of LiDAR and Terrestrial Laser Scanning (TLS) can be used in the measurement of the forest structure elements such as canopy height, plant density and basal area. The process of estimating the canopy height is easily done using the Canopy Height Model (CHM) that was generated from the LiDAR data. The plant counting that was required in determining the plant density of the forest was done by producing the individual tree crown delineation from the CHM that was generated in the previous stage. The TLS is used for extracting the diameter at breast height (DBH) value that was used for calculating the basal area of each tree of the forest. As a result, this study proved that laser scanning technologies of LiDAR and Terrestrial Laser Scanning has the capability in measuring the forest structure as the result of this study showed the optimum and positive result for all three forest structure elements. For canopy height, it shows the root mean square error (RMSE) of 5.4146, *t*-test of 0.004 and *p*-value of 0.997 which indicates the medium dependencies between the LiDAR and field measurement. The error that can contribute to this problem is the difficulties in determining the actual outmost canopy of the trees either using LiDAR or in the field measurement. For the plant density measurement, there is not much different between the field observation and the one that was generated from LiDAR as only ± one tree per m^2 for all tree plots. This is due to the capability of LiDAR to produce detailed and accurate Canopy Height Model (CHM) and individual tree crown delineation that indicate the number of trees in the forest that involved in plant density estimation. In basal area estimation, it proved that TLS is very reliable in measuring the DBH that used for computing the basal area calculation with RMSE of less than one for each plot (plot 1: 0.1789, plot 2: 0.3317, plot 3: 0.1671), t-test (plot 1: 0.984, plot 2: 0.873, plot 3: 0.012) and p-value (plot 1: 0.393, plot 2: 0.305, plot 3: 0.273). The TLS implementation in determining basal area of forest gave the accurate result as TLS can produced accurate DBH value that corresponding with the algorithm used. However, this study also found several limitations and shortage of both laser scanning technologies in handling the problem of very dense forest with many numbers of trees that have very close gap between each other that need to be solved with proper actions and solution as being applied in this study. Overall, this study had shown the use of laser scanning technologies in forest structure parameters measurement that must be done for forest management and preservation for future generation.

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