Assessing the uncertainty of tree height and Aboveground Biomass from Terrestrial Laser Scanner and Hypsometer using Airborne LiDAR data in Tropical rainforests

Sadadi Ojoatre, Ce Zhang, Yousif Ali Hussin, Henk Kloosterman, Ismail Mohd Hasmadi

***Abstract*—Tree height is one of the key parameters for estimating forest aboveground biomass (AGB). Traditionally, the tree height is measured by hypsometers, which are widely used to validate Terrestrial Laser Scanner (TLS) and Airborne LiDAR (ALS). However, the measurements from hypsometers are subject to huge uncertainties in comparison with TLS and ALS. The error associated with the height measurements propagate into the AGB estimation models, and eventually downgrade the accuracy of estimated AGB and the subsequent carbon stock. In this research, we test the use of Hypsometer, TLS and ALS in a tropical lowland rainforest to measure the height (H) and Diameter at Breast Height (DBH) and take Airborne LiDAR as a benchmark with high accuracy and fidelity in height measurements.**

The results revealed that, the field height measured by hypsometer underestimated the tree height with RMSE of 3.11, whereas the TLS underestimated height with RMSE of 1.61, when Airborne LiDAR was used as a benchmark to validate the field measurement and TLS. Due to significant differences in derived height measurements, the AGB and carbon stock also varied remarkably with values of 146.33 Mg and 68.77 Mg from field measurements, 170.86 Mg and 80.31 Mg from TLS, 179.85 Mg and 84.53 Mg using the Airborne LiDAR. Considering the Airborne LiDAR measurement as the most accurate, the AGB and carbon stock from field measurement represent 85.55% of total AGB and carbon stock estimation from Airborne LiDAR. Meanwhile, TLS measurements reflect 95.02% of AGB and carbon stock benchmarked with the measurements from Airborne LiDAR data. The results demonstrate the huge uncertainty in height measurement of large trees in comparison with small trees indicated by the significant differences. It was concluded that AGB and carbon stocks are sensitive to height measurement errors derived from various methods for measuring the tree height, the size of trees as large trees are difficult to measure height using hypsometer and TLS as opposed to small trees that are visible as well as the forest conditions. Compared with Airborne LiDAR, TLS achieved the higher accuracy of height estimation (R^2 = 0.91 with RMSE of 1.61) than the Hypsometer (R^2 =0.61 with RMSE of 3.11).

***Index Terms*—Tree height, accuracy, Tropical forest, Biomass, Carbon stock, Airborne LiDAR, Terrestrial Laser Scanner, Hypsometer and Error.**

I. Introduction

ACCURATE measurement of forest biomass and its dynamics is one of the grand challenges in tackling the global carbon emissions caused by deforestation and forest degradation [1]. To date, the most accurate measurement of aboveground biomass (AGB) would involve destructive methods by cutting the tree and weighing all parts, which is labour-intensive and time-consuming [2]. Alternatively, AGB can be estimated non-destructively through measurement of tree parameters such as diameter at breast height (DBH), tree height or wood density etc. These forest inventory parameters (e.g. tree height) have been derived by remotely sensed technologies in an automatic fashion, and further used as input variables for AGB estimation [3].

Airborne LiDAR (Light Detection and Ranging) is an active remote sensing technique that can provide appraisal of tree height [4]. Besides, terrestrial laser scanning (TLS) has been used for forest biomass assessment in recent years. The application of TLS provides a fast, efficient and accurate means for the determination of basic inventory parameters such as the number and the position of trees, DBH, tree height and crown shape parameters [5-12]. Both measurements from the airborne LiDAR and TLS require ground validation, however, the instruments used to carry out ground truth collection are subject to measurement errors.

Ground truth for tree heights are commonly measured indirectly through hypsometers. The hypsometers use trigonometric or geometric principles for tree height measurement [13]. These include: Abney level, Haga altimeter, Blume-Leiss altimeters and Suunto clinometer. Their measurement accuracy is approximately ± 1-2 meters [14]. However, Bonham (2013) indicates that, tree height may not be accurately measured by the hypsometers due to heterogeneity in the terrain and variation in heights of different tree species. Recently, hypsometers with a mixture of laser distance measuring and triangulation methods have been introduced with increased accuracy [16]. These include the laser distance

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S. Ojoatre is with the Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, U.K. (e-mail: o.sadadi@lancaster.ac.uk)

C. Zhang is with the Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, U.K. and the NERC Centre for Ecology & Hydrology, Library Avenue, Lancaster LA1 4AP, U.K. (e-mail: c.zhang9@lancaster.ac.uk)

Y. A. Hussin and E. H. Kloosterman are with the Department of Natural Resources, Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, Enschede 7500 AE, The Netherlands (e-mail: y.a.hussin@utwente.nl and e.h.kloosterman@utwente.nl)

I. M. Hasmadi is with the Department of Forest Production, Faculty of Forestry, Universiti Putra Malaysia (UPM), 43400 UPM, Serdang, Selangor Malaysia. (e-mail: mhasmadi@upm.edu.my)

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and range finders with accuracy of approximately ± 0.50 – 0.75 meters [17-19]. Laser device was also confirmed to be accurate when compared with clinometer instruments [20]. Despite the errors associated, the height measurements from the hypsometers are commonly used as the ground truth for validating remotely sensed data. However, the hypsometers possess measurement errors, and they could be biased depending on expertise and practical experience, without any standard acceptable accuracy for their measurement [21].

Nonetheless, Ene et al. (2012) empirically demonstrated that the Airborne LiDAR can offer very high accuracy for tree height measurement. This is because remotely sensed LiDAR avoids the problems of aerial triangulation and ortho-rectification, since each LiDAR point cloud is individually georeferenced and geometrically corrected. Andersen et al. (2006) assessed the accuracy of Airborne LiDAR with Validation data from a total station survey of individual tree to acquire highly accurate measurements of individual treetops which offers higher accuracy to reported accuracy for hypsometers. Also use of LiDAR to measure the height of features like buildings with highly accurate height measurements [23] provides the basis to use Airborne LiDAR measured height as a benchmark to validate tree height estimation from TLS and hypsometer. The laser system can estimate full spatial variability of forest carbon stock with low to medium uncertainties [24]. The uncertainties still exist because the forest AGB is relevant to several structural parameters such as DBH, tree height, wood density and branch distribution. However, tree height is the only structural parameter that is directly measured by the Airborne LiDAR [25]. Numerous studies have demonstrated that Airborne LiDAR can measure tree height accurately compared to field measurement [7, 26, 27, 28, 29].

Ensuring accuracy in height measurement is the fundamental concern since tree height contributes 50% towards estimating AGB and carbon stock in the allometric equation that are based on DBH and height only. Biomass estimation with tree height as an input provides more accurate result compared to those without height [30-32]. Inaccurate tree height measurement can, thus, lead to inaccurate estimation of the AGB and consequently carbon stock [33]. Although various studies have been undertaken on forest biomass estimation using Airborne LiDAR and TLS [3, 34], limited studies have assessed the accuracy of tree height measurement by combining ALS, TLS as well as hypsometer in a lowland tropical rainforest with high species diversity (e.g. in Ayer Hitam, Malaysia). Jung et al. (2011) estimated tree parameters in a relatively homogeneous forest. Hunter et al. (2013) assessed the accuracy of tree height measured from field using handheld Clinometer together with ALS data. However, the TLS has still not yet been widely used to measure the tree height by to-date [36], and the majority of the existing studies focused on single measurement (e.g. Airborne LiDAR), without considering different measurements and their underling uncertainties.

In this study, we assess the uncertainty in tree height measurements using ALS, TLS and hypsometer, respectively. We use Airborne LiDAR data as a benchmark to validate tree height measurement from TLS and Hypsometer. The objectives were to (1) determine the accuracy of TLS for measuring DBH in a tropical Lowland forest (2) assess the difference among the accuracy of tree height measurements from hypsometer, TLS and Airborne LiDAR systems (3) assess the variation in AGB and Carbon stock from different height measurements and (4) the influence of tree size in terms of accuracy in height measurement and the sensitivity of biomass to the errors and uncertainties of height (H) derived from the three different systems. Therefore, plots were scanned using TLS and the Airborne LiDAR to assess the accuracy of trees height, and the field tree height was measured by the Hypsometer (Leica DISTO 510). The AGB and carbon stock were estimated by using the tree DBH and height measurements. The variations of AGB were analysed with different sizes of the trees and their associated uncertainties.

II. MATERIALS AND METHODS

A. Study area

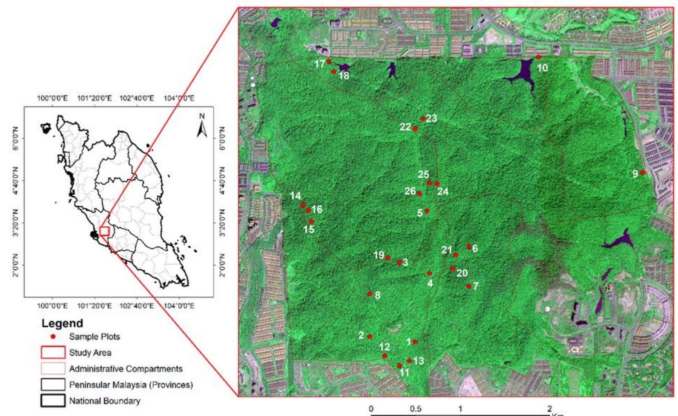


Fig. 1. Study area location map with sample plots that are coded with the plot numbers selected using a High resolution (50 cm) World View 3 satellite image.

Ayer Hitam tropical rainforest reserve is located in the southern part of Kuala Lumpur, Selangor, Malaysia centred at 3º 01´29.1" N 101º38´44.4" E (Figure 1). It covers about 1,176 hectares of pristine tropical rainforest with diverse tree species notably *Shorea spp.*, *Syzygium spp.*, *Makaranga spp.*, *Hopea sulcata*, *Artocarpus spp.*, *Endospermum spp*. and *Streblus elongatus* as the most dominant. The altitude of the forest ranges from 15 to 233 metres above sea level [37]. The average height of trees measured from the study area was 16 meters. The minimum and maximum temperatures within the study region range from 23°C to 32°C in average, and the annual precipitation is up to 1,765 mm with the peak between October and February [38]. The forest is one of the oldest low land tropical rainforest and was selectively logged several times from 1936 to 1965. It holds approximately 430 species of seed plants and 127 timber produced tree species [39]. The species distribution is highly diverse and heterogeneous with 100 plant species that are of medicinal, and at least 40 species of fern and their allies, as well as 43 species of moss diversity. Other diversity of plants comprises of rattans and orchids that are mostly of economic and ornamental value. The forest also contains endemics and rare species speckled across the region [40].

The forest has been managed by the Universiti Putra Malaysia after the agreement with the state government of Selangor in 1996. It has been administratively divided into three strata for management purposes, including burnt, high altitude and encroached. Figure 1 shows the location map of the study area.

B. Data and software used

In this research, 26 plots were sampled with the size of 500 m^2 in each plot from September 29, 2015 to October 12, 2015 in Ayer Hitam tropical rainforest reserve, with the sample plots coded with the plot numbers. Within each plot, DBH and tree height were measured for 312 trees using Hypsometer, TLS and ALS, respectively. DBH was measured at 130 cm height of each tree using diameter tape, and was measured using cylinder fitting method for TLS [41]. The tree height was only measured for those trees with DBH of ⩾10 cm and of merchantable size [42]. The TLS point cloud data was processed using RiSCAN Pro software (http://www.riegl.com/), and the measured Height was processed by the open source CloudCompare software (http://www.danielgm.net/cc/).

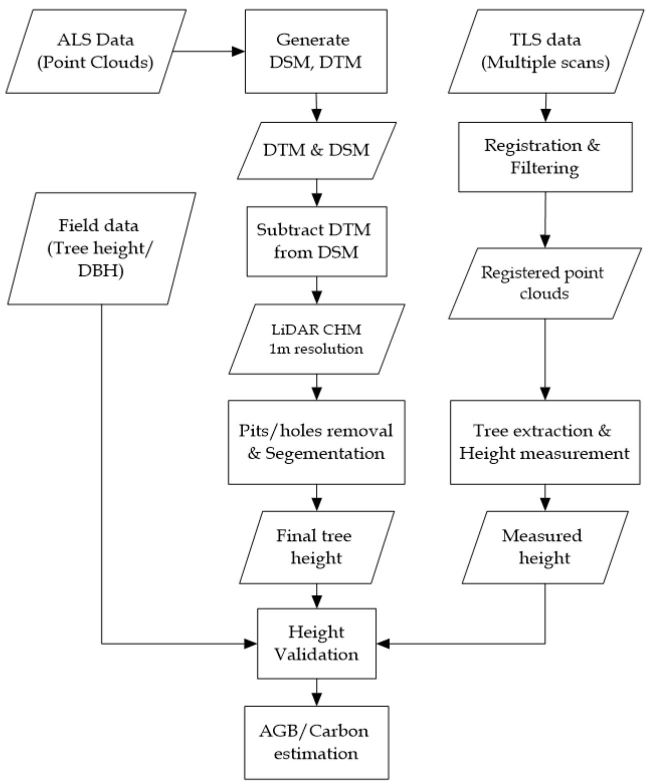


Fig. 2. Flowchart of the methods used in the study

The study also used Airborne LiDAR data acquired on July 23, 2013 using LiteMapper 5600 System with 5-6 points collected per square metre. The Airborne LiDAR data was processed by the LasTools software of rapidlasso GmbH (https://rapidlasso.com/LAStools/). The LiDAR Canopy Height Models (CHM) derived from LasTools was then segmented using the eCognition Software (http://www.ecognition.com/) to identify tree crowns and the respective heights. The methods and procedures are summarized in Figure 2.

C. Data Processing

Terrestrial Laser Scanner point cloud data was collected on 26 plots. Multiple scans (4 scan positions) within each plot (figure 3) were conducted in each plot using the RIEGL VZ-400 system with the maximum scan angle of 360 degrees, measurement rate of 42-122 (kHz) and line scan angle of 100 degrees with beam divergence of 0.35 mrad.

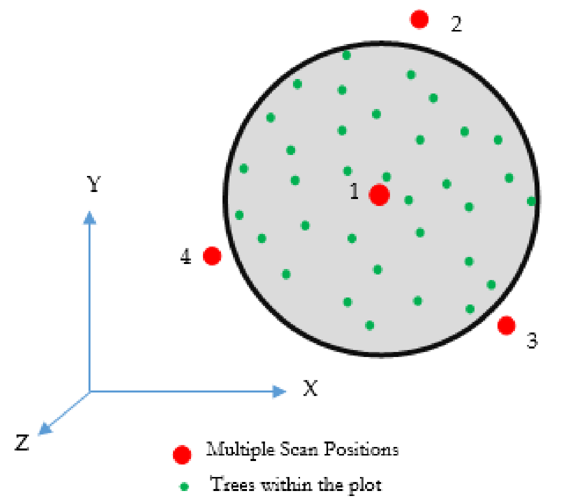


Fig. 3. Position of the multiple scan plots and circular layout of the plots for forestry inventory

The TLS collects data with full waveform with maximum range from 160 m to 350 m. It was also operated on high speed mode with precision and accuracy of 3 mm and 5 mm, respectively, in which 35 – 40 minutes were taken for each scan depending on the settings of the scanner.

The multiple scans were registered using the fine reflector scans (Cylinder and Circular) from the field with 15 tie points for each plot. Multiple station adjustment (MSA) was conducted with high accuracy indicated by low standard deviation (less than 0.013 meters) (Table 1). From the registered point clouds (Figure 3), trees were detected, identified and extracted.

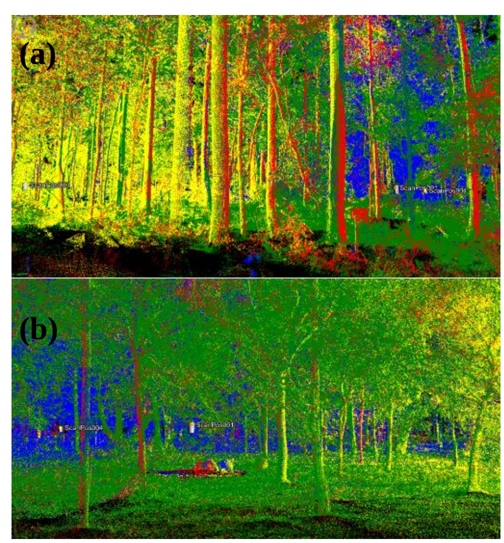


Fig. 4. 3D view of (a) plot 8 showing full view of the trees in the plot and (b) plot 9 showing the stem after multiple scan registration

TABLE I

MULTIPLE SCAN POSITION REGISTRATION AND ACCURACY IN STANDARD DEVIATION (STD. DEV.), WITH THE LEAST STD. DEV HIGHLIGHTED BY BOLD FONT.

Plot	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Std. Dev. (meters)	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. (meters)	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. (meters)	0.0179	0.0195	0.0163	0.0158	0.0184	0.0148	0.0169	0.0158	

The high accuracy of scan registration enables the appearance of the tree with all its branches and structure information such as actual shape. From the registered plots (Figure 4), the trees were manually extracted in 3D from the point cloud (Figure 5). The extraction process is very important since the trees are measured by the box method, in which a box is fitted around the tree to determine its height (Figure 6).

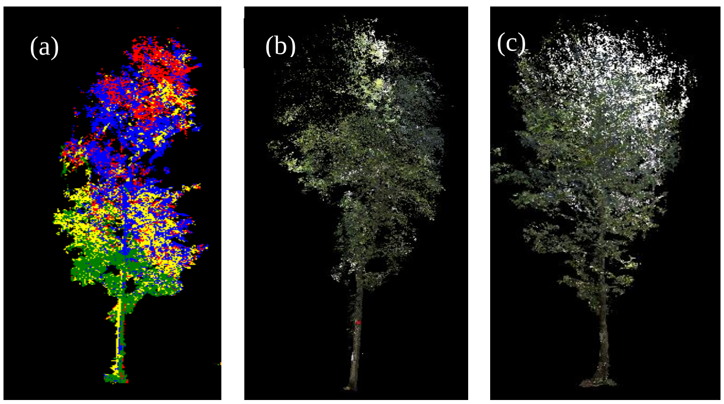


Fig. 5. A multi station adjusted tree (a) Tree No. 4 (Plot 13) displayed in multiple colours representing four different views of the same tree captured from four scan positions, and the (b) Tree No. 8 (Plot 11) and (c) Tree No. 13 (Plot 11) are characterising the 3D view of the trees at four different scan positions using natural colour. The natural colour here is the actual pictures of the mounted camera.

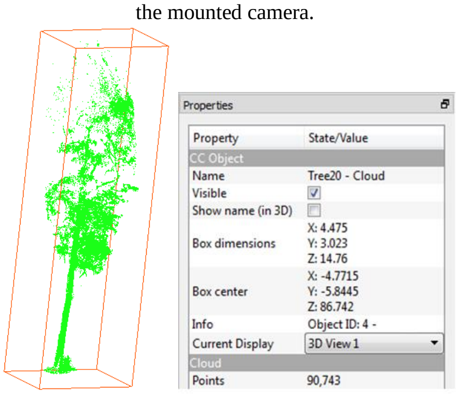


Fig. 6. Tree height measurement using box/cylinder method (Tree No. 20, Plot 10)

For Airborne LiDAR data, the Digital Surface Model (DSM) was generated by point clouds that involved the height between 0 and 50 metres. Using the DSM and Digital Terrain Model (DTM) of 1 metre resolution from which the Canopy Height Model (CHM) was created. The initially CHM has pits and holes in its visual effects. These pits and holes were removed by a pit free algorithm developed by [43] (Figure 7), with better performance in terms of smoothness
compared with other algorithms such as Gaussian smoothing.

The pit free CHM was then segmented using eCognition software to delineate the tree crowns. Tree peaks were identified and matched with the data collected from the field.

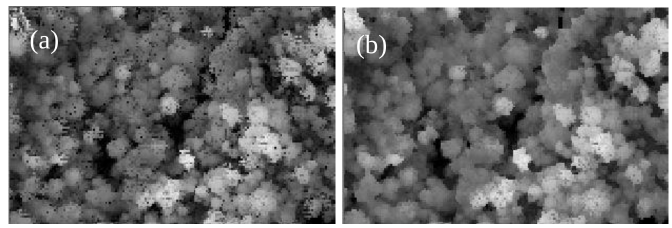


Fig. 7. (a) Airborne LiDAR CHM created by the LiDAR point clouds with pits and holes and (b) the processed LiDAR CHM using the pit free algorithm to smooth and remove noisy effects. The pit free CHM was then segmented to identify the tree tops.

To identify and match the trees measured from the field on the CHM, an Object Based Image Analysis (OBIA) approach was adopted, where the pit free CHM was segmented through Watershed segmentation to delineate individual tree crowns [44, 45]. The CHM was first segmented into coarse objects based on the nature of tree crowns observed in the plots during fieldwork. Such segmentation was further refined by the brightness of the pixels. The segmentation accuracy of the pit free CHM was assessed by using equations 1, 2 and 3.

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

$$Under\ segmentation = 1 - \frac{area(xi \cap yj)}{area(yj)} \quad (2)$$

$$D_{ij} = \sqrt{\frac{Oversegmentation_{ij}^2 + Undersegmentation_{ij}^2}{2}} \quad (3)$$

The pit free CHM was segmented with an accuracy assessed empirically by the goodness of fit (D-Value) that represents the measure of closeness (Equation 3). The obtained D-Value was 0.23, meaning that the segmentation was close to the manually delineated crowns with sufficient accuracy. The plots were delineated based on their various radius, and then integrated into the tree positions identified from the field and TLS measurements. The tree tops were then identified using maximal elevation [46]. The selected trees from each plot were identified using their number tags and the coordinates from the TLS point cloud. The centre coordinate of each plot was collected using the Magellan Mobile Mapper 6 with a stated accuracy of 1-2 meters [47]. The individual tree location was further confirmed by the number tag and location on the plot based on the TLS scan positions with the location of the tree in TLS scanner own coordinate (SOC) system.

The relationship between the heights measured by different methods (Hypsometer, TLS and ALS) were assessed statistically using analysis of variance (ANOVA), correlation, and linear regression were undertaken to test the accuracy of the measurements. A Root Mean Square Error (RMSE) (equation 4) to assess the accuracy.

$$RMSE = \sqrt{\sum_{i=1}^{n} (y_i - \hat{Y})^2 / n} \quad (4)$$

D. Aboveground biomass and carbon estimation

The AGB for individual trees was derived by using a generic allometric equation established by [48] (Equation 5), which is suitable to the mixed tree species. This model has been applied in Kalimantan, Indonesia by [50] and demonstrated robustness in AGB estimation. The inputs of the allometric equation were the DBH measured from the field, the wood density and height measured from Hypsometer, TLS and Airborne LiDAR measurements. Therefore, AGB was estimated for the three methods respectively using the corresponding height measurements while maintaining the same for the field measured DBH and wood density to obtain a controlled comparison. The results were compared statistically for significance.

$$AGB = 0.0509 \times \boldsymbol{\rho} D^2 H \quad (5)$$

Where AGB refers to the above ground tree biomass (kg); $\boldsymbol{\rho}$ (oven-dry wood over green volume) in g/cm3 obtained from Global Wood Density [51], D represents DBH (cm) and H denotes the height (m). This equation has been widely applied in tropical rainforest biomass estimation [48], and more specifically, the mixed tree species that are similar to our case has been applied by [52]. The carbon stock for the tree units were derived directly from the estimated AGB. Carbon content took approximately 50% of the total forest biomass according to the research by [53]. Therefore, a conversion factor was used to acquire the amount of carbon for the identified trees. In this study, a value of 0.47 was used strictly following the guidelines designed by Intergovernmental Panel on Climate Change [54]

$$C = B \times CF \quad (6)$$

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

III. EXPERIMENTAL RESULTS AND ANALYSIS

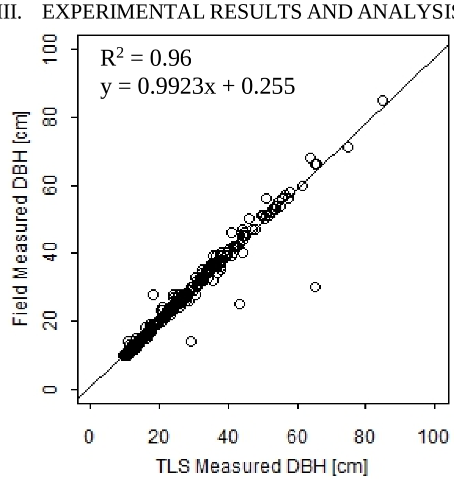
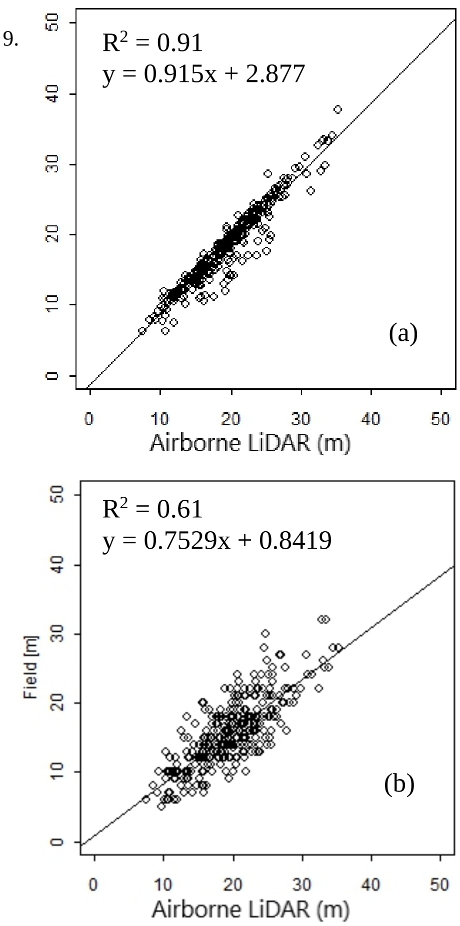


Fig. 8. Scatter plot for field DBH and TLS DBH.

Validation of the DBH was conducted by using the relationship between the field and TLS measurements. The field DBH was used as the independent (x) variable, whereas the TLS DBH measurement was used as the dependent (y) variable to assess their relationship. The DBH measured from the field was then used as an input of the allometric equation to estimate the AGB and the consequent carbon stocks. Figure 8 demonstrated that an extremely high R2 indicating the explained variances was achieved up to 0.96, with a correlation coefficient of 0.98 between the field DBH and the TLS measured DBH.

A. Accuracy of tree height

Fig. 9.



Comparisons between (a) TLS and Airborne LiDAR as well as (b) Field and Airborne LiDAR.

TABLE II
STATISTICAL ANALYSIS AMONG THREE TREE HEIGHT MEASUREMENTS (HYPSOMETER, TLS, AND AIRBORNE LIDAR) USING BASIC SUMMARY STATISTICS AND SINGLE FACTOR ANOVA.

	Height Measurements		
Statistic	Hypsometer	TLS	Airborne LiDAR
Mean	15.59	18.26	19.59
SD	5.02	5.46	5.23
Variance	25.22	29.78	27.32
Count	312	312	312

ANOVA						
Source of Variation	SS	df	MS	F	P-value	F critical
Between Groups	2,588.36	2	1294.18	47.16	0.05	3.01
Within Groups	25,602.18	933	27.44			

statistical differences in height were further tested using a single factor ANOVA to assess the variance of the means among three tree height measurements. From Table 2, the difference of the tree height is statistically significant, with P-value = 0.05 for the between-group variation with F value greater than $F_{critical}$.

B. Aboveground Biomass and Carbon estimation

The AGBs for the identified 312 individual trees were estimated by using the Allometric equation with the tree inventory parameters, including the DBH and height from field, TLS derived tree height as well as the tree height derived from the Airborne LiDAR CHM (Table 2). The global wood density (WD) of 0.57 [55], as a standard for Asia and South Eastern Asia, was used as an input to the allometric equation. The

carbon was derived as 47% of the above ground biomass (AGB) for the trees [54]. Consequently, based on the amount of AGB, there was also significant difference in the carbon stock between the different measurement with P-value = 0.05 (Table 2).

The amount of AGB (Table 2) derived from the tree height measurement using Hypsometer, TLS, and Airborne LiDAR were calculated, where significant difference (P-value = 0.05) was shown among these different measurements. The largest difference came from AGB from field and Airborne LiDAR measurement (18.6%), and the difference between AGB from field and TLS was also relatively high (14.36%). However, the AGB from TLS and Airborne LiDAR was the lowest (4.99%), meaning that there was no statistical significance between that of TLS and Airborne LiDAR. The TLS estimates 95.02% of AGB that was obtained from Airborne LiDAR, whereas the field height only estimated 81.29% of AGB benchmarked with Airborne LiDAR data.

TABLE III
ESTIMATED AGB AND CARBON FOR THE SELECTED TREES

Statistics	Field Measurement		TLS		Airborne LiDAR	
	Biomass	Carbon	Biomass	Carbon	Biomass	Carbon
Mean [Mg]	0.47	0.22	0.55	0.26	0.58	0.27
SD	0.62	0.29	0.74	0.35	0.76	0.36
Minimum	0.02	0.01	0.02	0.01	0.03	0.01
Maximum	5.87	2.76	7.13	3.35	7.23	3.40
Total [Mg]	146.33	68.77	170.86	80.31	179.85	84.53
Number	312		312		312	
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F critical
Between Groups	1.93	2	0.97	1.92	0.15	3.01
Within Groups	467.95	933	0.50			
Total	469.88	935				

The One-Way ANOVA did not show statistical significance for the three measurements (P=0.15), and a Paired t-Test was further conducted to assess the differences between different measurements, in which a significant difference was shown in AGB and Carbon stock between Hypsometer and Airborne LiDAR, TLS and Airborne LiDAR as well as Hypsometer and TLS measurements (Table 4).

TABLE IV
T-TEST FOR THE PAIRED TWO SAMPLE MEANS BETWEEN HYPSOMETER AND AIRBORNE LIDAR, TLS AND AIRBORNE LIDAR AS WELL AS HYPSOMETER AND TLS

	t-Test: Paired Two Sample for Means for AGB from the different measurements					
	Hypsometer	*ALS*	*TLS*	*ALS*	*Hypsometer*	*TLS*
Mean	0.47	0.58	0.55	0.58	0.47	0.55
Variance	0.38	0.58	0.55	0.58	0.38	0.55
Number	312	312	312	312	312	312
Correlation	0.98		0.99		0.98	
t Stat	-10.16		-8.82		-7.62	
P(T<=t)	3.82E-21		8.16E-17		3.11E-13	
t Critical	1.97		1.96		1.96	

The amount of AGB (Table 3) derived from the tree height measurement from Hypsometer (field), TLS, and Airborne LiDAR were calculated, and there was significant difference between these different measurements. The largest difference came from AGB from field and Airborne LiDAR measurement (18.6%), and the difference between AGB from field and TLS was also relatively high (14.36%). However, the AGB from TLS and Airborne LiDAR was the lowest (4.99%), meaning that there was no statistical significance between that of TLS and Airborne LiDAR. The TLS estimates 95.02% of AGB that was obtained from Airborne LiDAR, whereas the field height only estimated 81.29% of AGB benchmarked with Airborne LiDAR data.

Figure 10 shows the total AGB and carbon stock of the observed 312 trees. For the field height measurement, the AGB and carbon stock were 146.33 Mg and 68.77 Mg respectively. TLS measurement acquired 170.86 Mg and 80.31 Mg of the AGB and carbon stock, whereas the Airborne LiDAR (ALS) achieved 179.85 and 84.53 Mg for AGB and Carbon stock, respectively. The results showed that the ALS could obtain the highest AGB and Carbon stock, which is significantly higher than those of TLS and the field measurements, while the TLS was closer to the ALS in comparison with the field measurements.

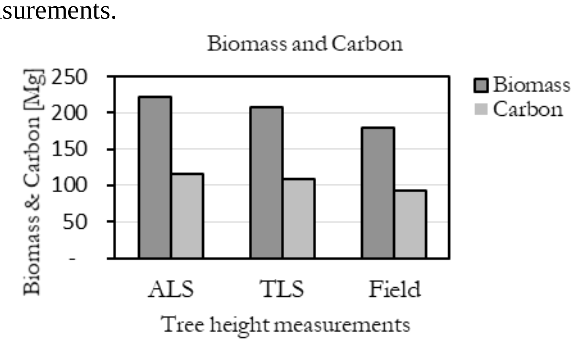


Fig. 10. Biomass and Carbon stock from Hypsometer (Field), TLS and ALS

C. Height accuracy, uncertainty and sensitivity analysis

The uncertainty within the tree height measurement comes from the instrument errors, the actual measurements, and the conditions of the forest, particularly the size of the tree (either large or small), canopy or crown structure, and altitude (slope)

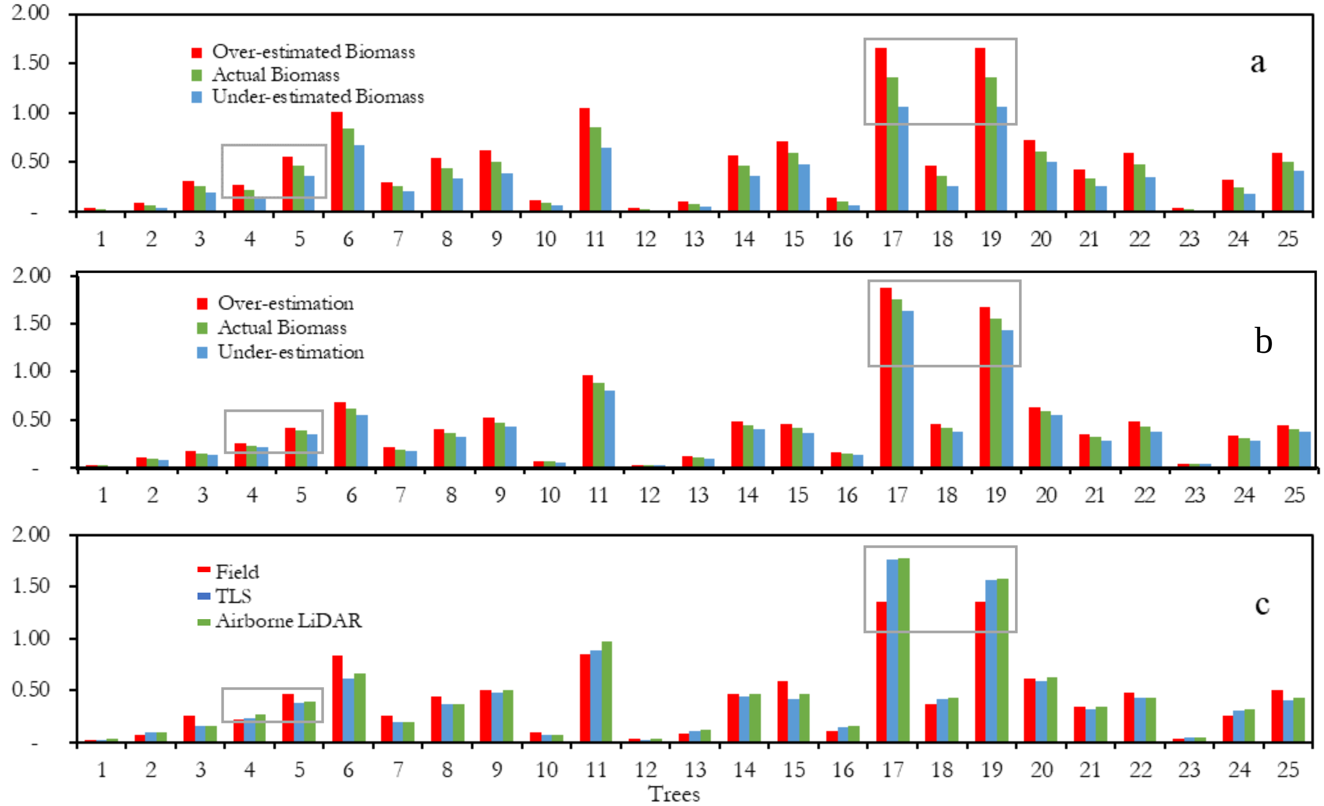


Fig. 11. a) Biomass variation by the accuracy of Hypsometer (±3.11m) to obtain under-estimation and over-estimation, respectively, with Airborne used as benchmark on each tree; b) Biomass variation by the accuracy of TLS (±1.61m) to obtain the under-estimation and over-estimation of AGB with Airborne LiDAR; and c) The actual Biomass variation from tree height measurements using Hypsometer, TLS and Airborne LiDAR

that hinders accurate tree height measurement [56]. These errors will propagate into the estimation of the AGB. In this study, the errors in tree height measurement were quantified to assess the influence on the overall estimation of AGB and carbon stocks. Tree biomass for 25 selected trees were shown with different methods, including field measurement with an adjusted height by ±3.11 m through RMSE (Figure 11a), TLS height measurement adjusted by an RMSE of ±1.61 m (Figure 11b). The sensitivity of AGB in terms of the field measured height, TLS measured height and Airborne LiDAR were tested (Figure 11c). In both cases, biomass was underestimated or over-estimated by the field measurement that was associated with standard errors of ±3.11 m and ±1.61 m for TLS in tree height measurement.

The large trees possess larger uncertainty in height measurement, since the AGB variation for large trees is larger in comparison with small trees (Figures 11a - c).

The size of tree height has great influence upon the uncertainty of tree height measurement. For instance, Tree No. 1 (figure 11a – c), shows low AGB variation due to the size and the small height while, tree 17 and 19 which shows high AGB variations. The variation in AGB for large trees is huge for all the methods used, and the AGB is highly sensitive to the different measurements. With the large trees, the TLS tends to record close measurements with Airborne LiDAR compared to field and LiDAR relationships. While the tree is small, all the methods tend to record close or similar amounts of AGB.

IV. DISCUSSION

DBH of trees with greater or equal to 10 cm were considered for the measurement using diameter tape [57]. It was also measured using the TLS through horizontal slicing at 130 cm height of the tree [5], and such measurement produced a highly accurate result with R^2 of 0.97 an a RMSE of 0.26, when validated by the field measured DBH. These results were comparable with [5], [59] and [41], who obtained R^2 ranging from 0.91 to 0.97 with TLS measured DBH validated using field measured DBH. Considering the high accuracy of the DBH from field, the study adopted the same field measured DBH to assess the AGB using different tree height measurements.

Tree height was measured by the Leica DISTO 510 laser distance (hypsometer), TLS as well as the LiDAR CHM. The Leica DISTO instrument uses a laser based technology. The tree height variation in different measurements in this study has been attributed to the operational mode of different methods. Distance from measured (branch/crown) and true horizontal distance to the crown could lead to unbiased errors [32]. This was also observed in situations where the tree trunks were not well projected, displacement of the crown tops from the trunk location as well as the size of the tree since small trees are easier and more accurate to be measured than the large trees. However, large trees can be measured accurately from Airborne LiDAR than the small ones through second or third return.

Ayer Hitam is a secondary tropical rainforest. Thus, occlusion of trees was the major challenges that cause difficulty in viewing the actual height or canopy top in order to measure the tree height precisely using the hypsometer. Therefore, the measured tree height was either over-estimated with adjacent tree top being captured or under-estimated while the laser hit on the branches, that were not the canopy top. Using the hypsometer requires unblocked path from the laser ranger to the top of the tree [60], which was observed during the field work in Ayer Hitam. Meanwhile for TLS, the trees were scanned from multiple scan points hence viewing of the same tree from different scan positions ensured the top of the tree is captured at least in one of the scans.

The height measurement using the Hypsometer resulted in R^2 of 0.61, correlation coefficient of 0.78 and RMSE 3.11 (21.44%), meaning that 78.56% accuracy validated by using the Airborne LiDAR. This was attributed to difficulties in observing the exact tree top due to the slope which has a potential influence on the height measurement and the occlusion of the crown structure. Slope introduces the displacement of the crown from the tree stand, which has a significant influence on the overall height measurement discussed similarly in [61]. Such result is also comparable with that of [62], in which a correlation ranging from 0.61 - 0.83 was obtained with varied elevations. The field height measured from Ultra Vertex Hypsometer was further validated through a CHM derived from stereo image matching with Airborne LiDAR, which produced higher measurement accuracy. The result could also be associated with the difficulties in viewing the top of the tree as measurements carried out in the field using the handheld hypsometer was reported a threshold accuracy of ±50 cm compared with the Airborne LiDAR, which views the top of the tree with a threshold accuracy of ±10 cm [7], [63].

The accuracy of field height measurement during this study falls below the previous studies, where other hypsometers like Clinometer were used for field data collection [64] with a standard error of 1.1 m (R^2 = 0.68). It should be noted that, the studies reported was carried out in temperate forests with plantation, where tree height is relatively the same compared with the tropical forest like Ayer Hitam with multiple tree layers and tree height differences. The field measured height results from this study compared with those of previous studies [7] indicated that field measurement had the lowest accuracy, which can be explained by the challenges in measuring tree height in multi-layer secondary tropical rainforest, where mixed canopies and occlusion of the tree top was commonly existed.

TLS height was much more accurate than the field measured height using hypsometer. The results indicated that the Airborne LiDAR derived height was highly correlated with the TLS height with R2 of 0.91 and RMSE of 1.61 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, minor difference between the TLS and Airborne LiDAR measurement was observed due to the limitation of laser pulse towards the tree top from the ground, especially the large trees that are fully viewed from the TLS scans. This can be explained by the laser pulse blocked by the leaves of the various layers in the tropical rainforest. Based on the accuracy and the potentials of the terrestrial laser scanning, the TLS method fills the gap between field measurements and Airborne LiDAR measurements by ensuring accurate assessment for the part below crown [10]. 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 less correlation compared with [41] with an accuracy of 92% of height and RMSE of 1.51. It can be argued that their study was done in a plantation forest with trees that have relatively similar heights, whereas this study was carried out in a secondary lowland tropical rainforest with multiple layers and considerable occlusion. Therefore, field height measurement was extremely difference when the definition of tree height was the distance between 2 horizontal planes from the bottom to the topmost of the tree. In such case, most of the tree tops cannot be clearly viewed by the TLS and the field measurements.

The Airborne LiDAR data was processed with 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 compared with manual digitisation). A total of 312 trees were matched on the CHM with TLS and field measurement. The Airborne LiDAR was further used to validate the field and TLS height measurements. The Airborne LiDAR estimated 78.56% of field measured tree height, while 93.24% of tree height measured was correctly estimated using the TLS. The process of the creating CHM involves DTM and DSM creation. Such processes also introduce uncertainty, especially in individual tree identification. The point clouds in the Las/Laz format are triangulated using triangular irregular network (TIN) to raster DEM and CHM, the accuracy was thus enhanced, and the quality was further improved by the LiDAR point density for the consequent CHM. The standard CHM contained pits and holes that could be associated with a combination of factors ranging from data acquisition to post processing [69]. [66] also explained that due to penetration of the laser pulse to the branches of trees, returns are not considered as first return on the CHM. These pits and holes were removed by the pit free algorithm developed by [43]. The pitfree algorithm was evaluated by 3x3 mean and Gaussian filters in [69]. The AGB for the individual trees was calculated by the allometric equation developed by [48], which requires tree DBH, height and wood density as an input. The wood density [55] specified for Asia and South Eastern Asia was adopted instead of the specific tree species wood densities as the focus of this research was to assess sensitivity of AGB to the tree height. Tree density also influences the accuracy of tree height measurement, and particularly, the high tree density could lead to occlusion that hindered the identification of tree from the TLS scans and LiDAR CHM, due to the difficulty in viewing of the exact tree top. AGB was calculated for 312 individual trees obtained in 26 plots with tree height measured from field, TLS and Airborne LiDAR. The field DBH 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 shows huge variation in the amount of AGB from both methods and the individual tree sizes. The large trees demonstrate huge variation in comparison with small trees. The Airborne LiDAR height was the most accurate measurement, where significant amount of biomass is lost when other measurements were used, especially 18.6% of AGB is lost while field tree height measurement is used for the allometric equation. Field measurement under-estimates the tree height by approximately ±3.12 RMSE with an R2 of 0.61. Meanwhile, the TLS measured tree height under-estimates tree height by ±1.66 RMSE and consequently underestimation of the AGB by 4.99%.

The variation in AGB is caused by height measurement variation and the corresponding tree size, which further affects the carbon stock that is derived directly from AGB. Carbon stock is approximately 50% of the tree AGB [54]. There was significant difference between the carbon stock from field, TLS and Airborne LiDAR. Field measurement under-estimated carbon stock, which is much more severe than the TLS measurement benchmarked with the Airborne LiDAR. In this study, the mean carbon stock per tree was 0.22 Mg for field height measurement, 0.26 Mg for TLS height, whereas the Airborne LiDAR was 0.27 Mg in average. Most of the existing studies for carbon stock mapping focused on the general carbon maps of the entire forest [68], while this study focused on the individual tree to understand the variation in the carbon stock from different measurements of the tree height, tree sizes and the associated uncertainties. The variation in the AGB based on the size of tree height shows that small trees can be accurately measured by the methods, whereas the large trees will pose challenges to be measured using the methods.

V. CONCLUSION

This study assessed the accuracy of height measurements from Hypsometer, Terrestrial Laser Scanner (TLS), and Airborne LiDAR in a tropical lowland rainforest. The Airborne LiDAR was used as the benchmark to validate the measurements from TLS and Hypsometers. Accurate measurements of tree height require the visibility on the top of the tree, which is hard to be captured using hypsometers, whereas the Airborne LiDAR provides overhead observations of the tree top, and TLS can capture the top through multiple scan positions. The study concludes that the tree height in tropical lowland rainforest can be measured using Terrestrial Laser Scanner (TLS), although Airborne LiDAR offers the best accuracy, TLS measures tree height more accurate than Hypsometers, particularly for large trees that are difficult to be measured from field. Owing to difficulties in measuring the heights of large trees, they are considered as the major cause of aboveground biomass variations in tropical forest. The smaller the tree, the less uncertainty was observed in tree height measurement. Large trees can be accurately measured by Airborne LiDAR, TLS, whereas the field-based measurements cannot accurately identify the exact tree height, which consequently affects the accuracy of the biomass estimation in tropical forests. Amongst these tree measurements, the Airborne LiDAR provides the most appropriate basis for validating the tree height measurement.

Based on this study, more researches can be carried out in the future to assess the complementarity of Airborne LiDAR and TLS, this is largely due to the strength of TLS in capturing the ground information (the crown stem) and the Airborne LiDAR capturing the tree top from the first returns. In addition, more studies can be conducted in modelling the tropical forest AGB using TLS, since its less widely applied in the tropical rainforests.

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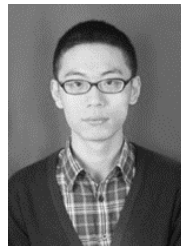
Sadadi Ojoatre received MSc Degree in Geoinformation Science and Earth Observation (Natural Resource Management) in 2016 from the Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, The Netherlands. He is now pursuing PhD degree at Lancaster Environment Centre, Lancaster University, UK. His major research interest lies in the application of geospatial technologies (Remote Sensing & GIS) to a wide range of fields especially forestry, land and water management.



Ce Zhang received PhD Degree in Geography from Lancaster Environment Centre, Lancaster University, U.K in 2018. He is now a senior (postdoctoral) research associate at Centre of Excellence in Environmental Data Science (*CEEDS*), a joint venture between Lancaster University and Centre for Ecology & Hydrology (CEH).
His major research interests include geospatial data mining, machine learning, deep learning and remotely sensed image analysis.

Yousif Ali Hussin received PhD Degree in Forest Sciences (Remote Sensing and GIS) from Colorado State University in 1990. He is an Associate Professor of Remote Sensing and GIS at the Department of Natural Resources, Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, The Netherlands.
His main research interest is the application of LiDAR, microwave and optical satellite data in monitoring tropical deforestation and forest degradation.

Henk Kloosterman is a Lecturer at the Department of Natural Resources, Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, The Netherlands. His research mainly focuses on vegetation and forest mapping and management.

Mohd Hasmadi Ismail received PhD Degree in Geoinformatics Technology from Cranfield University, UK in 2005. He is now a Professor of Geoinformatics Technology (Remote Sensing and GIS) at Universiti Putra Malaysia.
His research expertise is Geoinformatics (Remote Sensing and GIS) and Forest Harvesting.