Factual approach for tropical forest parameters measurement and monitoring: future option with a focus on synergetic use of airborne and terrestrial LiDAR technologies

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ABSTRACT
Forest biomass and carbon are critical for ecological monitoring, and yet poorly modelled in complex ecosystems such as the tropical rainforests. To overcome this challenge incurred due to the complex biophysical properties of tropical forests, Airborne and Terrestrial LiDAR (Light Detection and Ranging) technologies have been used combinedly. Airborne LiDAR data ‘from above’ are largely restricted to analyses of lower canopy layer trees. Its combination with Terrestrial LiDAR allows the assessment of tree crowns under the upper canopy layer, thus opening up new possibilities for a more complete assessment of all the trees in a multi-layer stand. In this study, Airborne LiDAR was used for upper canopy tree measurements while Terrestrial LiDAR was complimented for lower canopy layer trees. The result showed that LiDAR-based tree measurements of DBH and height were highly accurate. We highly improved the accuracy of estimated above-ground biomass (AGB)/carbon from 87% of Terrestrial and 90% of Airborne LiDAR-based estimates to 97% through combining the use of the two technologies. This approach contributes to the development of efficient techniques for forest monitoring systems and bears the potential to extend the modelling options from remote sensing data to understory layer trees.

1. Introduction
Accurate assessment of forest variables is crucial for any forest monitoring system conducted at local, regional, and global levels. Several approaches describing the vertical and horizontal canopy structures of forests are currently being used. Lu (2006) reported that the use of conventional field methods, geographic information systems, and remotely sensed data are common data sources. The determination of forest canopy dynamics and
forest metrics is often difficult to infer from remote sensing alone, because of the intrinsic complexity of forest structures (Larjavaara and Muller-Landau 2013; Réjou, Nicolas, and Pierre 2019). This structural complexity of forests leads to uncertainties in the estimation and extrapolation of remote sensing derived metrics, e.g. forest biomass or carbon balances, species diversity, and forest volume.

Accurate, efficient estimation of forest variables for structurally complex forests is now made available by advanced remote sensing technologies. Particularly, Airborne and Terrestrial LiDARs are capable of determining the vertical forest canopy structures, which contrasts with the spectral metrics from optical imagery that are usually affected by saturation problems in dense forests canopies. Several studies have confirmed that Airborne and Terrestrial LiDAR Scanning can provide highly accurate forest inventory parameters (e.g. Alexander et al. 2018; Larue et al. 2018; Otero et al. 2018; Ojoatre et al. 2019).

Airborne LiDAR determines the vertical structure of vegetation by measuring the distance between the sensor and a target. The laser points allow for the computation of a digital terrain model (DTM), digital surface model (DSM), and canopy height model (CHM). From the CHM, individual tree crowns can be delineated using region growing segmentation (Carleer and Wolff 2005), cone-shaped objects fitting through (Leeuwen, Coops, and Wulder 2010) or 3D canopy structure using individual tree detection (ITD) methods (Wang et al. 2016), and tree parameters can be measured or modelled. Although forest inventory with either Airborne or Terrestrial LiDAR is possible in forests with simple canopy conditions, in structurally complex forests, Airborne LiDAR point cloud data can only characterize the upper canopy (Wassihun et al. 2019). Terrestrial LiDAR can help extract forest metrics for the lower canopy layers (Lau et al. 2019).

Because of Terrestrial LiDAR is ground-based and thus provides much denser point cloud than Airborne LiDAR (Stovall, Anderson-teixeira, and Shugart 2018). Millions of points per square metre can be obtained with Terrestrial LiDAR which are highly suitable for describing 3D forest structures in details, especially for under-canopy trees. Forest metrics such as DBH and stem volume can be obtained efficiently using Terrestrial LiDAR and data analysing techniques, e.g. (Hopkinson et al. 2004), cylinder fitting (Bienert et al. 2006), circle fitting (Henning and Radtke 2006) or commercial software such as RiSCAN PRO (Bazezew, Hussin, and Kloosterman 2018).

In this study, we investigated the synergy of Airborne and Terrestrial LiDAR point cloud data for estimating biomass/carbon in a structurally complex tropical forest. Our method combined data from Airborne and Terrestrial LiDARs. Using combined 3D point cloud data, we detected individual tree crowns and estimated forest height, DBH and biomass for not only tall trees but also under canopy trees. We showed that the synergy use of the two types of LiDARs can overcome the challenges of estimation of tree metrics (e.g. crown delineation, tree height, DBH, and biomass/carbon) in structurally complex forest stands.

2. Materials and methods

2.1. Study site

The study was carried out at Ayer Hitam tropical forest reserve in the Selangor State of Malaysia (3°0’0” to 3°2’0” latitude and 101°38’0” to 101°40’0” longitude) (Figure 1). The
Forest covers an area of 1248 ha. The site is leased by the University of Putra Malaysia (UPM) since 1990 to be used for educational and research purposes.

The altitude within the study area ranges between 15 and 233 m a.s.l. The annual average temperature ranges from 23°C to 32°C with a high amount of monthly rainfall throughout the year (annual average precipitation of 1765 mm along higher precipitation befalls from October to February) (Hanum 1999).

2.2. Field data

Field data were collected in September and October 2016. A total of 27 circular sampling plots were used, each having an extent of 500 m² (12.62 m radius). In relatively steeply sloped areas, a slope correction factor was used to maintain a sampling projected area of 500 m² vertically projected. Field-based diameter at breast height (DBH), tree height, crown diameter, and individual tree locations were recorded with diameter-tape, Leica DISTO D510, Densiometer, and handheld Garmin GPS, respectively. Sampling units were nominated based on slope steepness and distance to the road where it was possible to carry the Terrestrial LiDAR, aiming at covering the variation in forest structures. A total of 786 trees with a DBH ranging from 10 to 84 cm were recorded in all sampling plots, which were used to validate the field- and LiDAR-based estimates.

2.3. Terrestrial LiDAR data and processing

Terrestrial LiDAR point cloud data were acquired using RIEGL VZ-400 Terrestrial Laser Scanner concurrently with field data collection. The instrument has a range from 1.5 to
600 m with a laser in the near-infrared wavelength range (1550 nm). It records multiple returns up to four per emitted pulse with data precision of 3 mm and an accuracy of 5 mm.

The scanning process was made in a multi-scan mode with four scanning positions, and a complete 360° scenes of the horizontal plane were collected at each scanning position. Three positions were situated at the outer side of the circular plot with 120° far apart, and one is located centrally. All trees inside the plot with DBH ≥ 10 cm labelled with A4 laminated numbers, which used to recognize the trees on point cloud and later linked to the corresponding field and Airborne LiDAR identified trees. The scanning was maintained with Panorama 60 resolutions across all plots, which offers acceptable laser return points. Each scanning position was also conveyed with 13 overlapping images with a digital camera mounted on the top of the instrument.

The coregistration process was done using reference targets or retro-reflectors. The registration of four scanning positions into one common reference system was executed using RiSCAN PRO software which allows marker-based automatic registration of point clouds. To minimize the errors in 3D coregistration, multi-station adjustment (MSA) was executed through an iterative closest point algorithm. The registered point cloud of each plot was then filtered to the extent of the circular plot (500 m²) by manually selecting the outer boundary using the spot of the outer scan positions. Figure 2 shows a sample 3D cluster and individual trees. Extracted individual trees DBH (at 1.3 m height from the ground) and height were then measured using the distance function in RiSCAN PRO software.

### 2.4. Airborne LiDAR data and processing

Airborne LiDAR dataset was collected in July 2013, by the University Putra Malaysia (UPM) using LiteMapper 5600 waveform-digitizing LiDAR system for terrain and vegetation mapping. The experiment covered 22 acquisition flights. The point cloud density was 5 to 6 points/m² with pulse rate varied from 70 kHz to 240 kHz and a wavelength of 1064 nm. The average flight height was between 700 and 1000 m.

The laser points were classified into ground and non-ground return components on using the progressive triangular network (TIN) method implemented in the LAStool software.

![Figure 2](image.png)

Figure 2. Registered sample plot based on four scanning positions; (a)- a registered 3D cluster of trees for sample plot (displayed in false colour); (b) and (c)- extracted individual tree displayed in true and false colour, respectively.
The first return laser points were interpolated into a regular grid representing the digital surface model (DSM) while the ground returns were interpolated into a digital terrain model (DTM). Forest canopy height model (CHM) was calculated as the difference between DTM and DSM (Figures 3 & 4). Pits in the CHM were filtered out using a pit-free algorithm (Khosravipour et al. 2014). Airborne LiDAR point clouds with height ≤0 m or ≥50 m were removed. Individual tree crowns were delineated from the Airborne LiDAR-CHM using region growing segmentation method in the eCognition software.

**Figure 3.** A subset of processed DSM, DTM, and CHM (established through subtracting DTM from DSM).

**Figure 4.** A subset of airborne LiDAR-CHM (a-'Las' format displayed in LasTool software; b- image in ‘Tiff’ format used for segmentation of individual tree crown).
2.5. Merging airborne and terrestrial LiDAR data

Synergetic use of Airborne and Terrestrial LiDAR requires co-registration of the two data sources. Trees identified from Airborne LiDAR-CHM were then connected to Terrestrial-detected tree stems for DBH use. To link trees detected from Airborne and Terrestrial LiDAR data with their corresponding field-censused trees, tree position, tree-labelling, and stem attributes measured in the field were used since GPS positions of trees measured under canopy layers are less accurate.

In this experiment, the Airborne and Terrestrial LiDAR tree height measurements were taken per the instrument’s potential of detecting treetops accurately. Thus, the forest structure was cross-sectioned into two canopies: viz. upper and lower canopies. Canopy cross-sectioning was executed by setting the minimum canopy height threshold that could be detected from Airborne LiDAR-CHM. The decision for average height-threshold was made based on the local maxima values from the segmented LiDAR-CHM or Canopy Projection Area (CPA). Then, trees with a canopy height below this threshold were considered as sub-canopy trees and height measurement was taken from the Terrestrial LiDAR data.

2.6. Biomass/carbon modelling with LiDAR technologies

At the individual tree and plot level, biomass estimation with traditional field-based, discrete use of terrestrial and Airborne LiDAR-based, and combination of Airborne and Terrestrial LiDAR approach were executed. The Terrestrial LiDAR or Airborne LiDAR-based AGB/carbon was computed using all tree stems and crowns that were identified from the point cloud dataset. Furthermore, the Airborne LiDAR was used for upper canopy trees height measurement and Terrestrial LiDAR for lower canopy tree parameters (stem measurement, and lower canopy trees height). We then regressed and compared the biomass-derived from LiDAR-based estimates to the biomass estimated from the traditional-field approach. We used a generic allometric equation for tropical forest developed by Chave et al. (2014) to estimate AGB (Equation (1)). The carbon content of the vegetation can be executed based on the IPCC (2006) conversion factor of 0.47.

\[
AGB = 0.0673 \times (\rho D^2 H)^{0.976}
\]  

where AGB-Above-ground biomass (kg); D-Diameter at breast height (DBH) (cm); H-height (m); and \(\rho\)-wood density (g/cm\(^3\)).

3. Results and discussion

3.1. LiDAR-based tree detections and tree measurements

In this study, 94% of the field recorded trees were recognized in the combined Airborne and Terrestrial LiDAR data. Of all the 786 field recorded trees, 451 (57%) and 290 (37%) trees with their crown-tops were identified by Airborne and Terrestrial LiDAR, respectively. Forty-five (6%) trees with a DBH of \(\leq 12\) cm distributed in 16 plots could not be visibly identified either by Airborne or Terrestrial LiDAR (Figure 5).
This can be explained by the fact that the study area is composed of multi-canopy layers of dense tropical forest. Thus, Airborne LiDAR-based detection was restricted to only trees in the emergent canopy layer. Hilker et al. (2010) also confirmed that Airborne LiDAR laser pulses were limited to upper canopy vegetation detection where below canopy trees are occluded by upper canopy layer crowns. On the contrary to this study, Naesset, Bollandsas, and Martin (2006) and Garcia et al. (2010) found that Airborne LiDAR data accurately identified more than 90% of the trees at different canopy layers in relatively heterogeneous spruce forests. In our study, highly overlapping crowns prevent the laser returns from penetrating the understory vegetation. Terrestrial LiDAR point cloud data offer accurate parameters for trees with a low canopy height for which Airborne LiDAR laser penetration and return is too weak, viz. stem characteristics and lower canopy trees height. The TLS-based measurement accuracy varied depending on the number of scanning positions. The point cloud data collection method through multi-scanning positions in our study site highly improved the accuracy of stem measurements. The study of Yun et al. (2019) confirmed that the application of multiple-scan position reduces the occlusion impacts and offered an improved 3D of individual trees. In our study, the instrument provides full 3D parts of the individual tree from the stump to approximately 12 m of the canopy height. Due to the occlusion caused by interlocking branches, the upper canopy trees height were under-sampled by the Terrestrial LiDAR.

The result also showed that Airborne and Terrestrial LiDAR offered an accurate DBH, height, and AGB estimates when both instruments were adapted to their crown-top detection potentials. Especially, Terrestrial LiDAR-based DBH estimates were highly similar to field-based diameter measurements (Table 1). We enhanced the precision through collecting point cloud from multiple scan positions and appropriate scanning distance (sample plot of 12.62 m radius were used). Methods of manual-based 3D
individual tree extraction and direct measurements from point cloud data through distance function algorithm using RiSCAN PRO also highly improved the DBH estimates.

The LiDAR-based tree heights were used to validate field height measurements which were obtained using handheld Leica DISTO DS10 (Table 1). There was a statistically significant difference between field-based and LiDAR-derived heights (at a 95% level of confidence). The reason being field tree height measurements were highly vulnerable to the occlusion effects of tree canopies. We noted that finding a occlusion-free position to view the treetops with the handheld height measuring instrument is challenging in dense tropical forests.

We investigated the ability of Airborne and Terrestrial LiDAR-based forest biomass retrieval both as discrete and synergy use techniques. The summary of the regression model for the field and LiDAR-estimated AGB is shown in Table 1. Accordingly, the estimated AGB/carbon was highly improved from R² 0.87 of Terrestrial and 0.90 of Airborne LiDAR-based estimates to 0.97 through synergetic use of two laser technologies. About 7% and 10% of unexplained AGB form Airborne and Terrestrial LiDAR, respectively, was explained by the combined approach. The error associated with the empirical regression model of AGB is mainly associated with errors incurred in traditional field-based height measurements. According to Hunter et al. (2013), height error ranging from 3% to 20% contributes to 5–6% of uncertainty in estimated biomass. In our study, field height measurement error ranges from approximately 14% (lower canopy trees) to 20% (higher canopy trees).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>R²</th>
<th>r</th>
<th>RMSE</th>
<th>RMSE (%)</th>
<th>Bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>DBH (Terrestrial LiDAR Vs. Field)</td>
<td>0.97</td>
<td>0.99</td>
<td>1.302</td>
<td>6.74</td>
<td>−0.58</td>
</tr>
<tr>
<td>Upper Canopy Trees Height (Airborne LiDAR Vs. Field)</td>
<td>0.63</td>
<td>0.80</td>
<td>3.722</td>
<td>19.99</td>
<td>−1.10</td>
</tr>
<tr>
<td>Lower Canopy Trees Height (Terrestrial LiDAR Vs. Field)</td>
<td>0.71</td>
<td>0.91</td>
<td>1.323</td>
<td>14.12</td>
<td>0.34</td>
</tr>
<tr>
<td>AGB (Terrestrial LiDAR Vs. Field)</td>
<td>0.87</td>
<td>0.97</td>
<td>1.027</td>
<td>13.42</td>
<td>0.06</td>
</tr>
<tr>
<td>AGB (Airborne LiDAR Vs. Field)</td>
<td>0.90</td>
<td>0.97</td>
<td>0.884</td>
<td>11.77</td>
<td>0.045</td>
</tr>
<tr>
<td>AGB (Airborne and Terrestrial LiDAR Synergy Vs. Field)</td>
<td>0.97</td>
<td>0.99</td>
<td>0.588</td>
<td>7.45</td>
<td>−0.27</td>
</tr>
</tbody>
</table>

Measurement units for DBH, height, and AGB is in cm, m, and Mg, respectively.

3.2. AGB estimations and accuracy

AGB estimation was conducted for individual trees in all plots. Height measurements for upper canopy trees were extracted from Airborne LiDAR data whereas those for lower canopy trees were extracted from Terrestrial LiDAR data. AGB of single trees were summed up to form AGB at the plot level.

Airborne and Terrestrial LiDAR estimated 247.15 Mg AGB stored in the 27 plots (183.07 Mg/ha of AGB or 86.04 Mg/ha of carbon). Among these, 228.02 Mg (92%) (168.90 Mg/ha of AGB or 79.38 Mg/ha of carbon) were contributed by the upper canopy layers-computed from Airborne LiDAR point cloud data. Only 19.13 Mg (8%) of AGB (14.17 Mg/ha of AGB or 6.66 Mg/ha of carbon) were from the lower canopy trees estimated from Terrestrial LiDAR point cloud data. A mean AGB of 168.80 and 14.20 Mg/ha was estimated for upper and lower canopy layer trees, respectively. This implies that it was able to capture an average of 14.20 Mg/ha of AGB with the complement of Terrestrial LiDAR. Figure 6 illustrates the overall portion of AGB at
different canopy conditions between Airborne LiDAR, Terrestrial LiDAR, and traditional field methods. Based on field-methods, a total of 220.76 Mg of AGB estimates in all plots (163.2 Mg/ha of AGB or 76.86 Mg/ha of carbon) was obtained. This infers field methods underestimated the AGB by 19.55 Mg/ha (9.55 Mg/ha of carbon) ~11% of total AGB.

The ability of LiDAR techniques to measure forest biomass/carbon mapping depends on the structural complexity of the studied forest. Individual tree crown detection rates with different laser technologies may differ in temperate and tropical forests. In this study, we confirmed the ability of Airborne and Terrestrial LiDAR techniques for retrieval of forest parameters and AGB/carbon. Moreover, the synergetic use the two LiDAR technologies offer more accurate estimation of AGB than being used alone. The accuracy of synergy-based AGB estimation showed that traditional-field-based AGB estimations were under-estimated because field-based height measurements were largely erroneous (Table 1). In the study of Kankare et al. (2013), AGB was estimated from the Airborne LiDAR data with high accuracy, and similarly from Terrestrial LiDAR dataset (Olsoy et al. 2014) with $R^2$ of 93%, but in temperate forests. On the other hand, Ioki et al. (2014); and Laurin et al. (2014) used single LiDAR (using LiDAR sensor ALTM GERMINI) in multilayered tropical forests and they obtained a lower accuracy for biomass estimation. We found that combining Airborne and Terrestrial LiDAR data for tropical forests produced more accurate AGB or carbon stock estimation.

4. Conclusion

This study has offered for estimating AGB/carbon in structurally complex tropical forests with multi-canopy layers. Neither Airborne nor Terrestrial LiDAR can recognize more than two-thirds of the trees. The synergetic use of Airborne and Terrestrial LiDAR has made it possible to identify a tree number comparable to field records. In particular, Terrestrial LiDAR can complement Airborne LiDAR to DBH estimates and height measurements of understory trees.
The LiDAR technologies used in this study add to evidence that the approach offers basic forest metrics (height, DBH, and AGB) with high accuracy. The accuracy of field-based individual tree height measurements were largely in accurate (RMSE ranged between 1.30 and 3.72 m) when compared to Airborne and Terrestrial LiDAR-based measurements. The accuracy of DBH estimates from Terrestrial LiDAR point cloud data was highly similar field measurements. Terrestrial LiDAR dataset processing through RiSCAN PRO software using a distance function method also increased the accuracy significantly.

In this study, individual tree parameter estimates in the case of complex canopy structure of tropical forests offer a strong indication for the potential of integrating both LiDAR technologies. The combined use of Airborne and Terrestrial LiDAR based on the corresponding detecting potential of canopy structures offer a factual means for remotely sensed forest parameters assessments at an individual tree and plot level. The method can also be extended to accurately predict other forest metrics, such as basal area, stand density, and volume. More investigation is required for the Terrestrial LiDAR data acquisition from multiple scanning viewpoints to reduce the occlusion.

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