

Modeling Mangrove Above-Ground Biomass Using Terrestrial Laser Scanning Techniques: A Case Study of the *Avicennia marina* Species in the Bang Pu District, Thailand

Intarat, K.^{1,2} and Vaiphasa, C.^{2*}

¹Geography Sector, Faculty of Liberal Arts, Thammasat University, Pathum Thani, Thailand
E-mail: intaratt@tu.ac.th

²Department of Survey Engineering, Chulalongkorn University, Bangkok Thailand
E-mail: chaichoke@hotmail.com

*Corresponding Author

Abstract

*Deterioration of tropical mangrove forests is one of the most serious problems of the world's coastal ecosystems. Mangrove above-ground biomass (AGB) modeling is the key to support the management and rejuvenation of these ecosystems. Nevertheless, it is illegal to observe tree data using the destructive methods in reserved mangrove forests for acquiring tree allometric models. Thus, this study proposed a non-destructive alternative, the use of a terrestrial laser scanner (TLS) technique. The study site dominated by *Avicennia marina* (Forsk.) Veirh (*A. marina*) was located in the Bang Pu conservation area, Thailand. The tree structures were quantified and tested in this study. A Quantitative Structural Model (QSM) was chosen for the calculation of the tree stem volume. Then, the TLS allometric model was generated via a power function. The RMSE between the presented model and the four reference *A. marina* models were reported in this study. The largest RMSE errors (i.e., 40% and 35%) were found when comparing the TLS allometric model to the two generic allometric models. On the other hand, the outcomes of the species-specific models were closer to the outcome of this study (i.e., the RMSE errors are less than 20%). The disagreement between the proposed TLS model and the generic mangrove model suggested that a species-specific model is needed for more accurate results. It is anticipated that the methodology presented in this study may be used as standard procedures for producing the *A. marina* allometric model in other areas.*

1. Introduction

Mangrove ecosystems have extensive benefits at the world-wide scale (Lee et al., 2014). They are not only stabilizing the link between terrestrial and aquatic environments but also the highest potential source of carbon sequestration which can store higher carbon stock comparing to other terrestrial forests (Donato et al., 2011, Hamdan et al., 2013 and Hirata et al., 2014). However, both natural and anthropogenic disturbances, (e.g., sea-level rise, agriculture, and aquaculture) are causing mangrove reduction approximately 30-40% of the worldwide wetland (Ellison, 2015, Giri, 2016, Li et al., 2015 and Thu and Populus, 2007). As a result, efficient forest management techniques are needed to monitor the fluctuation of this important carbon mass (i.e., the above-ground biomass (AGB)). The AGB sampling can either be done destructively or non-destructively. The destructive sampling methods require harvesting the tree samples and bringing them back to the laboratory. Then, stems,

branches, leaves, and roots are separated and used for determining fresh weight. The dry weight is then converted via a dry-to-fresh weight ratio.

This process is illegal to perform in forest conservation areas. Moreover, it is laborious and not cost-effective. On the other hand, the non-destructive approach involves collecting physical tree data such as Diameter at Breast Height (DBH), tree height, stem curve, stem volume estimation, tree class, canopy layer, and wood specific density (WSD) (Liang et al., 2016) from the field without abolishing the tree samples. Next, with certain distortion, the relationship between the AGB and the physical tree components are calculated via either stochastic or non-stochastic models (Chave et al., 2014, Kenzo et al., 2009 Komiyama et al., 2008 and 2005; Njana et al., 2016, Ostadhashemi et al., 2014 and Vashum, 2012). In other words, the collected tree parameters are expected to be mathematically fitted with the chosen allometric models and the

residual standard error (e.g., root mean square error) are then reported (Comley and McGuinness, 2005, Komiyama et al., 2005, Laongmanee, 2011 and Patil et al., 2014). Nonetheless, there is no general rule for building such a complex mathematical relationship for the AGB estimation as various tree species and different characteristics of samples have to be considered (Chave et al., 2014). The mathematical models are usually customized for specific scenarios (Feliciano et al., 2014).

One of the key aspects is the ability of the terrestrial laser scanner (TLS) technology to accurately capture point cloud data in three-dimensional space. This makes possible the construction of the allometric model of individual trees. Additionally, the tree canopy gap and leaf distribution can also be correctly assessed using the TLS approach. Over the last decade, TLS technology has been developed for the operational use in forest inventory. The improvement for tree attributes acquisition and the automatic cloud points processing (Liang et al., 2016) are at the cutting edge of the laser scan technology. As for mangrove-specific studies, it has been reported that associating the high-resolution TLS measurements with field observations leads to the construction of a reliable allometric model (Feliciano et al., 2014), tree attributes measurement, and management plans and operational forestry (Liang et al., 2016). Unfortunately, there are very few reports on applying the TLS technology to different species of tropical mangroves. Thus, more studies are therefore needed to make this conclusive. As a result, this study is aimed to move one step closer to the conclusion. In other words, it aims to test the capability of the cutting-edge TLS technology if the high-resolution laser scanner can help to construct a correct allometric model for tropical mangrove species. The selected study area is the Bang Pu

mangrove conservation in Samut Prakan Province, Thailand. The area is homogeneous mangrove forests containing one dominating species, *Avicennia marina* (Forsk.) Veirh (*A. marina*). Thus, this is suited for constructing a single species allometric equation. The allometric model accuracy is to be finally tested against the published allometric models (Comley and McGuinness, 2005, Komiyama et al., 2005, Laongmanee, 2011 and Patil et al., 2014).

2. Study Area

The study site locates in the Recreation and Convalescence at Bang Pu in Samut Prakan Province, Thailand with coordinate N 13°30'59" and E 100°39'23" (Figure 1a). It is one of the first urban educational centers for mangrove ecosystems in Thailand (Parr et al., 2012). This study area is managed by the Foundation for Environmental Education for Sustainable Development (FEED), Thailand. A mangrove species that dominates the study area (i.e., the red dot in Figure 1a) is *Avicennia marina* (Forsk.) Veirh. It is commonly known as grey mangrove, and it can grow as a shrub or tree to a height up to 14 m in tropical regions.

The leaves are thick and can be five to eight cm long with vibrant, glossy green on the upper surface. It has aerial roots (pneumatophores) which can grow 20 cm height from the ground for absorbing oxygen during the tidal level rise. The species covers almost 90% of the mudflat area. Other species, for examples, *Rhizophora apiculate* Blume (Tall-stilt mangrove), *Rhizophora mucronata* Poir (Red mangrove), and *Avicennia alba* Blume (Black mangrove) are also sporadically found along the border of the study area. For the purpose of visualization, an example of the study scene is demonstrated in Figure 1b.

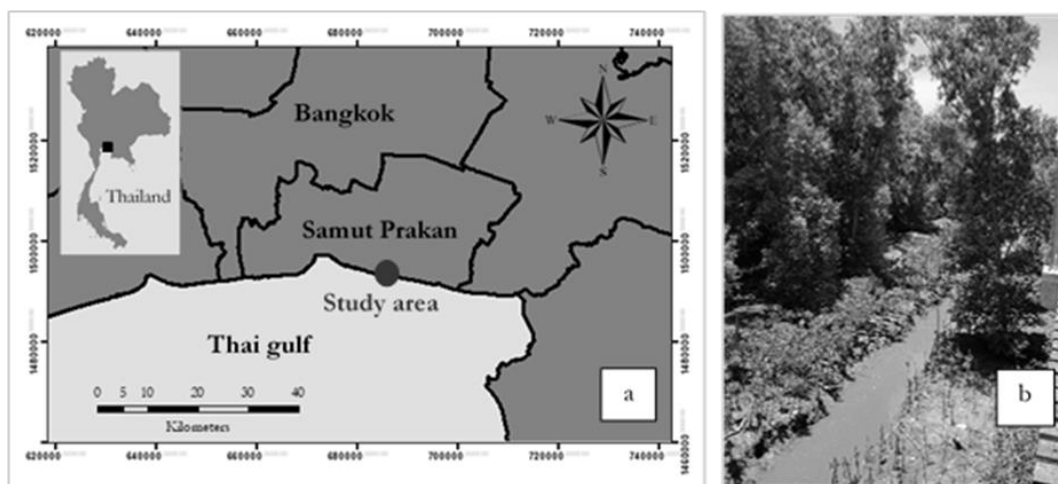


Figure 1: (a) Bang Pu mangrove conservation; (b) An example of *A. marina* observation sites

3. Method

3.1 Terrestrial Laser Scanner Data Observation

The TLS instrument used in this study is Topcon GLS2000 that respects the requirements of forest measurement benchmarks (Maas et al., 2008). The technical specifications of the instrument are presented in Table 1. The observation was conducted in August 2017 between 9 am to 3 pm that was at the time of the lowest tide. Thirty *A. Marina* samples (i.e., tree height > 1.5 m) have been selected and assigned the names starting from AM01 to AM30. These trees samples were randomly selected from the sampling site. Each location of the trees was collected using the real-time kinematic (RTK). The positional accuracy is within 5 cm. The sampling procedures were conducted under the guidelines (Feliciano et al., 2014). The DBH values were measured using a measurement tape and the heights were measured from TLS. The measured DBH values (cm) and heights (m) were reported in Table 2.

Following the guidelines (Feliciano et al., 2014), for each individual tree, at least three TLS scanning stations were installed at different angles. At least four tie points were required for the process of point cloud registration. Before conducting the scanning

process, the upper-left and lower-right boundary of the scene had to be specified. Then, the object in the boundary was targeted and scanned using a multi-pulse and high-resolution mode of the Topcon GLS2000 instrument. This chosen scanning resolution was approximately 6.3 mm at a distance of 10 m away from the target. The scanning process took about 26 minutes per scan at this resolution. During this process, the hemispherical image of the target was also taken. Lastly, each point cloud was automatically assigned with a color value so as to create the hemispherical image of the target in three-dimensional space using Topcon ScanMaster V.3.0 software.

3.2 Point Cloud Data Processing and Tree Volume Modelling

3.2.1 Registering and merging the cloud points

At each plot, all point cloud data were registered and merged from multiple-point-cloud images (Figure 2a) into one single point cloud image (Figure 2b). In this study, the registration residuals (i.e., root mean square errors) were kept to be smaller than 0.08 m. The leaves and canopies were then excluded from the final product (Figure 2c).

Table 1: TLS Topcon GLS2000 technical specifications compared to the minimum requirement

Specification	Topcon GLS2000
Range (m)	210
Scan resolution (mm)	4
Scan rate (points/sec)	120,000
Field of view	Hemisphere
Laser class	3R (eye safe)
Wavelength (nm)	1,064
Special features	Integrated camera, Touch display

Table 2: The measured DBH values and heights of the sample trees

Observation	DBH (cm)	Height (m)	Observation	DBH (cm)	Height (m)
AM01	18.81	10.70	AM16	19.19	10.99
AM02	26.57	10.50	AM17	26.50	11.23
AM03	20.24	11.41	AM18	23.78	11.04
AM04	14.03	11.55	AM19	23.91	10.65
AM05	20.62	13.52	AM20	16.40	9.91
AM06	14.80	7.73	AM21	20.04	10.84
AM07	19.86	11.31	AM22	26.75	10.33
AM08	11.90	6.13	AM23	16.55	10.33
AM09	13.30	7.14	AM24	17.69	11.84
AM10	12.42	6.88	AM25	16.04	10.19
AM11	24.67	10.74	AM26	15.91	10.75
AM12	25.31	10.66	AM27	26.17	11.05
AM13	15.97	10.33	AM28	22.12	10.55
AM14	24.11	10.10	AM29	21.70	10.73
AM15	20.96	10.55	AM30	16.03	10.43

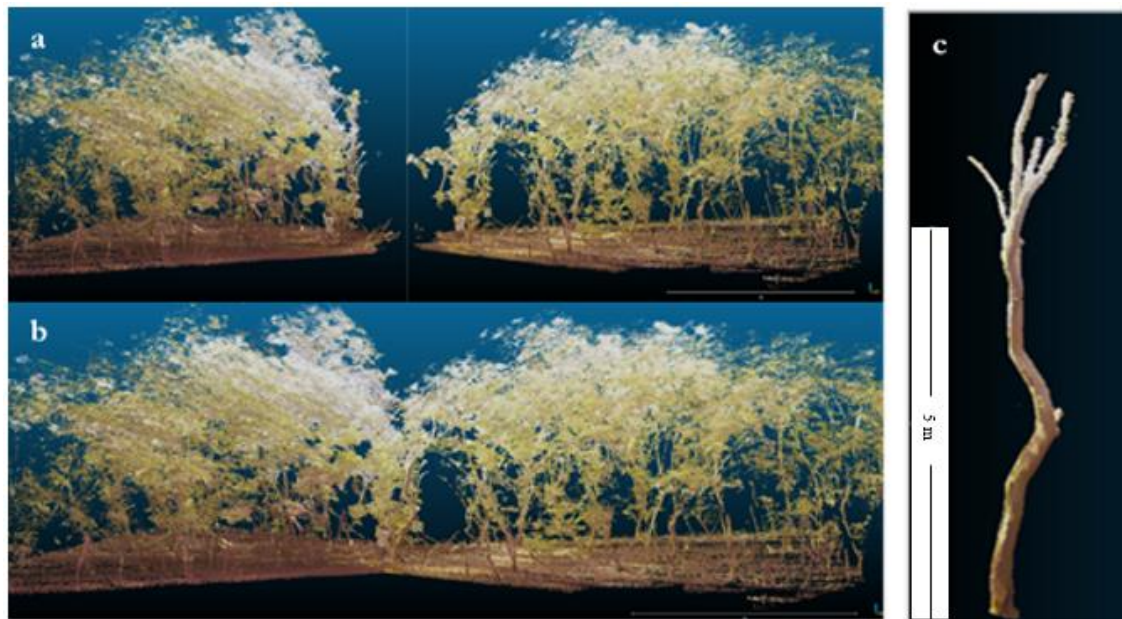


Figure 2: (a) An image of multiple point clouds before registering and merging; (b) A single point cloud image after merging; (c) An image of *A. marina* cloud points after excluding leaves and canopies.

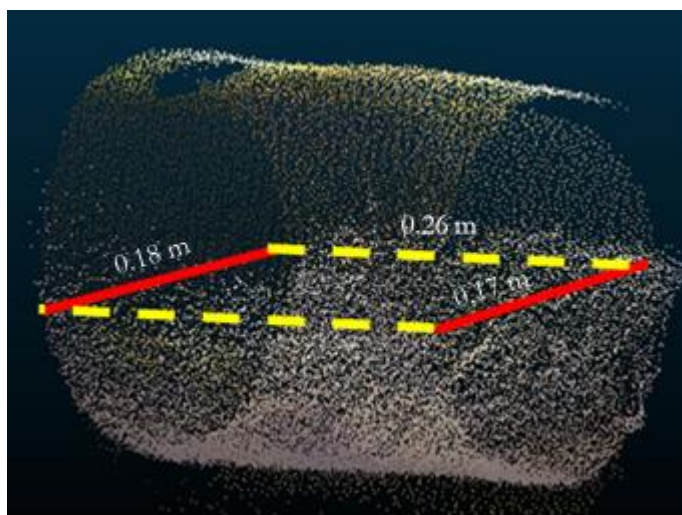


Figure 3: An image of a frustum showing the length (i.e., dash-yellow line) and the diameters of both ends (i.e., solid-red lines)

3.2.2 Segmentation and volume estimation of main stems

Each of the thirty trees was segmented into small but straight sections (i.e., frustums) and measured before calculating the total volume. This process was designed to reduce the problem of measuring the curved stems. The measurement was done under the environment of the Cloud Compare software. First, each frustum was visualized using the software, as seen in Figure 3. Then, the length and the two diameters at the two ends of each frustum were repeatedly measured for 30 times.

The standard errors of the measurements were reported. Next, the Smalian's formula (Feliciano et al., 2014) was then modified and used for estimating the parabolic frustum volume (i.e., the cylindrical segmentation volume). Please see the details of the modified Smalian's formula in Equation (1).

$$V = \frac{(A_T + A_B)}{2} \times h = \frac{\left(\frac{\pi D_T^2}{4} + \frac{\pi D_B^2}{4}\right)}{2} \times h$$

Equation 1

Where V indicates the volume of the segmented frustum. A_T and A_B were top and bottom cross-sectional areas. D_T , and D_B were diameters of the upper and bottom section. Lastly, the total volume of each tree was calculated by adding all of the individual frustum volumes. This calculation can be named the quantitative structural model (QSM) (Owers et al., 2018).

3.3 AGB Estimation and Allometric Model from TLS Data

3.3.1 Stem AGB estimation

In this study, the WSD of the *A. marina* species reported by Njana et al. (2016) was used for the estimation of the AGB. The total stem volume was multiplied by the WSD value (i.e., 0.60 g/cm³). It was reported that the chosen WSD has an uncertainty of 8.33% (Njana et al., 2016).

3.3.2 Total AGB estimation

Since the study areas were covered by dense mangrove forests, the TLS observations of each targeted tree were obstructed by the adjacent canopies. The canopy correction constant had to be applied in order to compensate for the obstruction effects. In other words, the correction constant was multiplied to the stem AGB value so as to obtain the total AGB. This study adopted the constant (i.e., 1.25) reported by Feliciano et al., (2014) and applied to all samples. The constant was derived from the statistics that the missing AGB was approximately missing by 10% to 30% of the total tree AGB (Feliciano et al., 2014 and Komiyama et al., 2005). The total AGB was calculated as in Equation (2):

$$AGB_{Total} = AGB_{stem} \times Correction_{canopy}$$

Equation 2

Where AGB_{stem} represents the AGB calculated in the previous section and $Correction_{canopy}$ is the 1.25 value.

3.3.3 Allometric modeling

In general, the allometric model is a non-linear equation (Sileshi, 2014). The power function is one of the most popular models used for constructing the non-linear relationship between the AGB and the tree component (Chave et al., 2005, Feliciano et al., 2014, Maan et al., 2015, Njana et al., 2016 and Olagoke et al., 2016). Thus, a power function was selected in this study for building the relationship between the estimated total AGB values and the measured DBH values. The power function in use was shown in Equation (3):

$$F(x) = a \times x^b$$

Equation 3

Where $F(x)$ represents AGB, x represents DBH, a indicates an allometry coefficient, and b indicates the proportionality between cumulated variables.

3.3.4 Referenced allometric models

Since the tree sampling scheme of this work is non-destructive, the accuracy assessment has to be done indirectly. In other words, the AGB estimated in this work is to be compared with the published results rather than compared with the real testing samples collected from the study area. This assessment is similar to the procedures found in the guidelines (Feliciano et al., 2014). Consequently, the estimated model of this study is to be compared with four published tropical mangrove allometric models. The first two models were published by Komiyama et al., (2005) and Laongmanee (2011), which were general mangrove allometric models as in Equation (4) and Equation (5). The third model was an Australian *A. marina* allometric models (Equation (6)) created by Comley and McGuinness (2005). The final model presented by Patil et al., (2014) was calculated using an Indian *A. marina* species (Equation (7)).

$$W_{top} = 0.251\rho D^{2.46}$$

Equation 4

$$W_{top} = 0.251\rho D^{2.24}$$

Equation 5

$$W_{top} = 0.3404D^{2.0273}$$

Equation 6

$$W_{top} = 0.308D^{2.11}$$

Equation 7

Where W_{top} is AGB, D represents DBH, and ρ which found in Equation (4) and Equation (5) represents WSD.

3.4 AGB Uncertainty Estimation

There are three major errors propagated in the stem AGB estimation: the diameter variations, the height discrepancies, and the WSD error. To evaluate these combined uncertainties, the error propagation theory (Chapra and Canale, 2010) has been adopted for this purpose. This combined effect of the three errors is shown in Equation (8).

$$\frac{\delta AGB_{stem}}{|AGB_{stem}|} = \sqrt{2\left(\frac{\delta D}{D}\right)^2 + \left(\frac{\delta H}{H}\right)^2 + \left(\frac{\delta WSD}{WSD}\right)^2}$$

Equation 8

Where $\frac{\delta D}{D}$, $\frac{\delta H}{H}$, and $\frac{\delta WSD}{WSD}$ denote the relative error of measured parameters for paraboloidal estimation. Then, the error of the stem AGB estimation (Equation (8)) and the canopy correction variance were combined via Equation (9) to produce the total uncertainty of the AGB estimation. This study adopted the range of the canopy variance suggested by the references (Feliciano et al., 2014 and Komiyama et al., 2005). It was found that the uncertainty of canopy correction is about 10% of the total AGB estimation.

$$\delta AGB_{Total} = \sqrt{(\delta AGB_{stem})^2 + (\delta AGB_{canopy})^2}$$

Equation 9

Where δAGB_{Total} represents total uncertainty of individual *A. marina* tree AGB, δAGB_{stem} represents an AGB stem uncertainty and δAGB_{canopy} represents a canopy correction uncertainty.

4. Result

4.1 AGB Estimation and Uncertainty

The results of the total AGB estimation for each of the tree samples were reported in the last column of Table 3. Then, the uncertainty of the total AGB estimation was calculated using Equation (8) and Equation (9). Uncertainties can occur from tree parameters' measurement for examples, height, diameter, WSD, and canopy correction. These discrepancies were 0.63%, 0.80%, 8.33%, and 10.00%, respectively. Thus, the total AGB uncertainty of this study was 13.08%. These

propagated uncertainties were represented as the plus-minus suffix in the last column of Table 3.

4.2 Comparing Allometric Models

The AGB estimates were fitted together with the DBH measurements to form a power function Equation (10). This power function has been compared with the other four allometric models (Comley and McGuinness, 2005, Komiyama et al., 2005, Laongmanee, 2011 and Patil et al., 2014). The comparison was depicted in Figure 4.

$$AGB_{Am} = 0.02746 \times DBH^{2.862}$$

Equation 10

Where AGB_{Am} represents the allometric model of *A. marina* tree in the study area and DBH represents the Diameter at Breast Height as a predictive variable. For the purpose of evaluation, the TLS measurements were presented as dots together with the variance bars in Figure 4. The estimated regression line (i.e., the power function of Equation (10)) is shown as a solid red line. The dash lines were the referenced models. Then, the RMSE between the presented model and the four referenced models were calculated.

The worst RMSE, the largest discrepancy, (i.e., 39.88%) was found between the presented model and the Komiyama et al., (2005), Figure 4(d). Comparing between the presented model and Laongmanee (2011), Figure 4(c) and between the presented model and Patil et al., (2014), Figure 4(b), resulted in the RMSE discrepancies of 35.12% and 19.72%, respectively. The lowest RMSE discrepancy of 13.30% was found when comparing with Comley and McGuinness (2005), Figure 4(a).

Table 3: Results of the AGB calculation and their corresponding DBH values

Observation	DBH (cm)	AGB Total (kg)	Observation	DBH (cm)	AGB Total (kg)
AM01	18.81	108.69 ± 14.25	AM16	19.19	128.90 ± 15.55
AM02	26.57	336.84 ± 44.33	AM17	26.50	325.44 ± 42.57
AM03	20.24	160.66 ± 21.05	AM18	23.78	239.93 ± 31.38
AM04	14.03	42.70 ± 5.59	AM19	23.91	240.23 ± 31.42
AM05	20.62	63.59 ± 21.45	AM20	16.40	81.29 ± 10.63
AM06	14.80	69.87 ± 9.13	AM21	20.04	155.00 ± 20.73
AM07	19.86	47.11 ± 19.24	AM22	26.75	329.37 ± 43.08
AM08	11.90	25.86 ± 3.39	AM23	16.55	83.37 ± 10.91
AM09	13.30	43.09 ± 5.64	AM24	17.69	105.69 ± 13.82
AM10	12.42	35.75 ± 4.68	AM25	16.04	81.53 ± 10.66
AM11	24.67	268.33 ± 35.10	AM26	15.91	76.52 ± 10.01
AM12	25.31	289.64 ± 36.58	AM27	26.17	310.49 ± 40.61
AM13	15.97	75.06 ± 9.82	AM28	22.12	201.90 ± 26.41
AM14	24.11	248.49 ± 32.50	AM29	21.70	184.70 ± 22.46
AM15	20.96	167.51 ± 21.91	AM30	16.03	80.77 ± 10.56

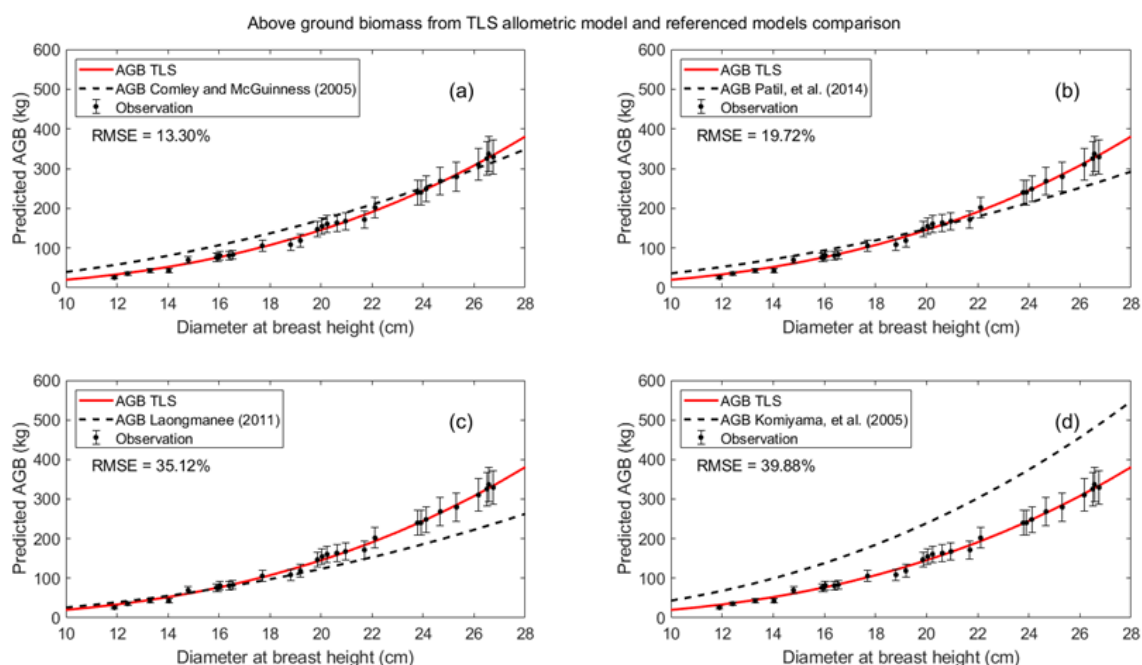


Figure 4: The regression models between the DBH and the total AGB calculated of this study was illustrated in a solid line. Tree observations (black dots with variance bars) were derived from the TLS estimation. The four referenced models: (a) Comley and McGuinness (2005), (b) Patil et al., (2014), (c) Laongmanee (2011), and (d) Komiyama et al., (2005) were displayed in the dash lines for the purpose of comparison

5. Discussion and Conclusion

The capability of cutting-edge TLS technology has been tested in this study. The high-resolution laser scanner helps construct an accurate allometric model for the tropical *A. marina* tree. This claim is supported by the small estimated uncertainties reported in Table 3 (i.e., less than the published threshold of 15% (Chave et al., 2005, Feliciano et al., 2014 and Hackenberg et al., 2015) and the agreement between the proposed model and the well-established model (Feliciano et al., 2014). The proposed allometric model of the *A. marina* trees is demonstrated in Figure 4.

The model presented by Comley and McGuinness (2005), Figure 4 (a), has the closest relationship to the proposed model. The RMSE discrepancy between the two lines was as low as 13.30% because the sizes of the *A. marina* trees of both areas are rather similar. The DBHs of both areas are between 11 and 30 cm, approximately. This evidence suggested that there may be a relationship between the mangrove sizes and the RMSE discrepancies. This was noticeable when comparing the results of this study to the areas that possess different tree sizes (Laongmanee, 2011 and Patil et al., 2014). For example, the Patil et al., (2014) stands, Figure 4(b), are mid-size mangrove holding the average DBHs about 19 cm where the

relation found the most agreement (i.e., where the two lines cross each other). There is no surprise that the results of this work are not in agreement with the generic mangrove model Komiyama et al., (2005) in Figure 4(d) and Laongmanee (2011) in Figure 4(c), respectively) as the generic models were constructed from a variety of mangrove species other than *A. marina*. This poor result suggested that a species-specific model may be needed for constructing the TLS model. Since the study area is one of Thailand nature reserves, destructive samplings are not allowed. Thus, a non-destructive assessment was alternately used. It was done by comparing our model with the four published works. This relative approach is deemed to have small drawbacks as the four referenced models were constructed from tropical mangrove data. Specifically, the models of Comley and McGuinness (2005) and Patil et al., (2014) were constructed from the tropical *A. marina* data.

According to the guidelines (Liang et al., 2016 and 2018), there are two options for tree attribute measurements, the single tree and the individual tree method. The first maximizes the number of cloud points per record as only one tree is scanned in several directions. The densely scanned cloud points provide possibilities in constructing a detailed 3-D model of the tree. However, this method requires

much time per treatment. The latter method, the individual tree measurement, scans many trees in a forest plot at once. Each plot incorporates at least five TLS stations. Combining many trees per scan is the advantage of this method as it reduces the time required per treatment. Nonetheless, the occlusion effect is the key problem when using this method (Feliciano et al., 2014 and Liang et al., 2016 and 2018). It can be corrected by adding extra TLS stations per plot to resolve the occlusion errors when measuring the forest as densely populated as Bang PU mangrove conservation.

The tree AGB estimation from cloud points can be computed using the tree shape simulation. It employs the geometric procedure to calculate the tree volume. Then, multiplying the estimated tree volume by the WSD for converting to the AGB. The typical method which is often used is the quantitative structural model (QSM). It geometrically transforms each frustum to the volume and subsequently incorporate with the WSD. The computation resulted in the AGB of each frustum. Alternative tree volume estimation incorporates with the 3-D reconstruction modeling (i.e., the Poisson surface reconstruction model (Kazhdan et al., 2006), which linearly reconstruct the noisy cloud points into the triangular mesh).

Thus, Owers et al., (2018) unveiled their experiment that the tree volume estimation between the QSM and the complex 3-D reconstruction surface model were not significantly different. When considering our study area, the trees in the plot are sizeable that easy to geometrically measure the represented cloud points. The primary geometric measurement is reliable enough to model the tree volume. Therefore, this study selected the QSM instead of the complex 3-D reconstruction modeling to measure the attribute's geometry for each frustum. However, there should be some further consideration on the mathematics of surface reconstruction model (Berger et al., 2013 and 2017 and Zhou and Koltun, 2013) that is suitable for any specific species. Further experiments on alternative surface reconstruction models are recommended.

This study proposes a TLS technique for quantifying the AGB of the *A. marina* trees of the Bang Pu conservation area, Thailand. A QSM method was chosen for the calculation of the tree stem volume. Then, the allometric model is generated via a power function. The RMSE between the presented model and the four reference *A. marina* models were reported. The largest error was found when comparing the presented model to the two generic allometric models (Komiyama et al., 2005 and Laongmanee, 2011), respectively. On the other hand, the outcome of the species-specific

models was closer to the outcome of this study (i.e., the RMSE errors are less than 20%). The disagreement between the proposed TLS model and the generic mangrove model suggested that a species-specific model is needed for more accurate results. It is anticipated that the methodology presented in this study may be used as a guideline for producing the *A. marina* allometric model in other areas.

Acknowledgements

The authors would like to delightfully thanks to Topcon Instrument Thailand for supporting the TLS for field observation. Thanks also go to the Foundation for Environmental Education for Sustainable Development (FEED) at Bang Pu mangrove conservation for facilitating the study location.

References

- Berger, M., Levine, J. A., Nonato, L. G., Taubin, G. and Silva, C. T., 2013, A Benchmark For Surface Reconstruction. *ACM Trans. Graph.*, Vol. 32(2), 1-17. doi:10.1145/2451236.2451246.
- Berger, M., Tagliasacchi, A., Seversky, L. M., Alliez, P., Levine, J., Sharf, A. and Silva, C., 2017, A Survey of Surface Reconstruction from Point Clouds. *Computer Graphics Forum*, Vol. 36(1), 301-329. doi:10.1111/cgf.12802.
- Chapra, S. C. and Canale, R. P., 2010, *Numerical Methods for Engineers*: Boston : McGraw-Hill Higher Education, c2010. 6th ed.
- Chave, J., Andalo, C., Brown, S., Cairns, M. A., Chambers, J. Q., Eamus, D., Fölster, H., Fromard, F., Higuchi, N., Kira, T., Lescure, J. P., Nelson, B. W., Ogawa, H., Puig, H., Riéra, B. and Yamakura, T., 2005, Tree Allometry and Improved Estimation of Carbon Stocks and Balance in Tropical Forests. *Oecologia*, Vol. 145(1), 87-99. doi:10.1007/s00442-005-0100-x.
- Chave, J., Rejou-Mechain, M., Burquez, A., Chidumayo, E., Colgan, M. S., Delitti, W. B. and Vieilledent, G. 2014, Improved Allometric Models to Estimate the Aboveground Biomass of Tropical Trees. *Global Change Biology*, Vol. 20(10), 3177-3190. doi:10.1111/gcb.12629.
- Comley, B. W. T. and McGuinness, K. A., 2005, Above- and Below-Ground Biomass and Allometry, of Four Common Northern Australian Mangroves. *Australian Journal of Botany*, Vol. 53(5), 431-436. doi:10.1071/bt0-4162.

- Donato, D. C., Kauffman, J. B., Murdiyarso, D., Kurnianto, S., Stidham, M. and Kanninen, M., 2011, Mangroves among the Most Carbon-Rich Forests in the Tropics. *Nature Geoscience*, Vol. 4(5), 293-297. doi:10.1038/ngeo1123.
- Ellison, J. C., 2015, Vulnerability Assessment of Mangroves to Climate Change and Sea-Level Rise Impacts. *Wetlands Ecology and Management*, Vol. 23(2), 115-137. doi:10.1007/s11273-014-9397-8.
- Feliciano, E. A., Wdowinski, S. and Potts, M. D., 2014, Assessing Mangrove Above-Ground Biomass and Structure using Terrestrial Laser Scanning: A Case Study in the Everglades National Park. *Wetlands*, Vol. 34(5), 955-968. doi:10.1007/s13157-014-0558-6.
- Giri, C., 2016, Observation and Monitoring of Mangrove Forests Using Remote Sensing: Opportunities and Challenges. *Remote Sensing*, Vol. 8(9). doi:10.3390/rs8090783.
- Hackenberg, J., Wassenberg, M., Spiecker, H. and Sun, D. J., 2015, Non Destructive Method for Biomass Prediction Combining TLS Derived Tree Volume and Wood Density. *Forests*, Vol. 6(4), 1274-1300. doi:10.3390/f6041274.
- Hamdan, O., Khairunnisa, M. R., Ammar, A. A., Hasmadi, I. M. and Aziz, H. K., 2013, Mangrove Carbon Stock Assessment by Optical Satellite Imagery. *Penilaian Stok Karbon Hutan Paya Laut Menggunakan Imej Satelit Optik.*, Vol. 25(4), 554-565.
- Hirata, Y., Tabuchi, R., Patanaponpaiboon, P., Pongparn, S., Yoneda, R. and Fujioka, Y., 2014, Estimation of Aboveground Biomass in Mangrove Forests Using High-Resolution Satellite Data. *Journal of Forest Research*, Vol. 19(1), 34-41. doi:10.1007/s10310-013-0402-5.
- Kazhdan, M., Bolitho, M. and Hoppe, H., 2006, Poisson Surface Reconstruction. *Paper Presented at the Proceedings of the Fourth Eurographics Symposium on Geometry Processing*, Cagliari, Sardinia, Italy.
- Kenzo, T., Ichie, T., Hattori, D., Itioka, T., Handa, C., Ohkubo, T. and Ninomiya, I. 2009, Development of Allometric Relationships for Accurate Estimation of Above- and Below-Ground Biomass in Tropical Secondary Forests in Sarawak, Malaysia. *Journal of Tropical Ecology*, Vol. 25, 371-386. doi:10.1017/s0266-467409006129.
- Komiyama, A., Ong, J. E. and Pongparn, S., 2008, Allometry, Biomass, and Productivity of Mangrove Forests: A Review. *Aquatic Botany*, Vol. 89(2), 128-137. doi:10.1016/j.aquabot.2007.12.006.
- Komiyama, A., Pongparn, S. and Kato, S., 2005, Common Allometric Equations for Estimating the Tree Weight of Mangroves. *Journal of Tropical Ecology*, Vol. 21, 471-477. doi:10.1017/s0266467405002476.
- Laongmanee, W., 2011, *Remote Sensing Techniques for Biomass Estimation of Mangrove Plantation (PhD.)*, Chulalongkorn University, Bangkok. Available from EBSCOhost cat05085a database.
- Li, S. S., Meng, X. W., Ge, Z. M. and Zhang, L. Q., 2015, Evaluation of the Threat From Sea-Level Rise to the Mangrove Ecosystems in Tieshangang Bay, Southern China. *Ocean & Coastal Management*, Vol. 109, 1-8. doi:10.1016/j.ocecoaman.2015.02.006.
- Liang, X., Kankare, V., Hyypä, J., Wang, Y., Kukko, A., Haggrén, H., Yu, X., Kaartinen, H., Jaakkola, A., Guan, F., Holopainen, M. and Vastaranta, M., 2016, Terrestrial Laser Scanning in Forest Inventories. *Isprs Journal of Photogrammetry and Remote Sensing*, Vol. 115, 63-77. doi:10.1016/j.isprsjprs.2016.01.006.
- Liang, X. L., Hyypä, J., Kaartinen, H., Lehtomäki, M., Pyörala, J., Holopainen, M., Brolly, G., Francesco, P., Hackenberg, J., Huang, H., Hyun-Woo, J., Katoh, M., Liu, L., Mokroš, M., Morel, J., Olofsson, K., Poveda-Lopez, J., Trochta, J., Wang, D., Wang, J., Xi, Z., Yang, B., Zheng, G., Kankar, V., Luoma, V., Yu, X., Chen, L., Vastaranta, M., Saarinen, N. and Wang, Y., 2018, International Benchmarking Of Terrestrial Laser Scanning Approaches for Forest Inventories. *Isprs Journal of Photogrammetry and Remote Sensing*, Vol. 144, 137-179. doi:10.1016/j.isprsjprs.2018.06.021.
- Lee, S. Y., Primavera, J. H., Dahdouh-Guebas, F., McKee, K., Bosire, J. O., Cannicci, S. and Record, S., 2014, Ecological Role and Services of Tropical Mangrove Ecosystems: A Reassessment. *Global Ecology and Biogeography*, Vol. 23(7), 726-743. doi:10.1111/geb.12155
- Maan, G. S., Singh, C. K., Singh, M. K. and Nagarajan, B., 2015, Tree Species Biomass and Carbon Stock Measurement Using Ground Based-LiDAR. *Geocarto International*, Vol. 30(3), 293-310. doi:10.1080/10106049.2014.925003.
- Maas, H. G., Bienert, A., Scheller, S. and Keane, E., 2008, Automatic Forest Inventory Parameter Determination from Terrestrial Laser Scanner Data. *International Journal of Remote Sensing*, Vol. 29(5), 1579-1593. doi:10.1080/01431160-701736406.

- Njana, M. A., Meilby, H., Eid, T., Zahabu, E. and Malimbwi, R. E., 2016, Importance of Tree Basic Density in Biomass Estimation and Associated Uncertainties: A Case of Three Mangrove Species in Tanzania. *Annals of Forest Science*, Vol. 73(4), 1073-1087. doi:10.1007/s13595-016-0583-0.
- Olagoke, A., Proisy, C., Feret, J. B., Blanchard, E., Fromard, F., Mehlig, U., Machado, de Menezes, M. M. dos Santos, V. F. and Berger, U., 2016, Extended Biomass Allometric Equations for Large Mangrove Trees from Terrestrial LiDAR Data. *Trees-Structure and Function*, Vol. 30(3), 935-947. doi:10.1007/s00468-015-1334-9.
- Ostadhashemi, R., Shahraji, T. R., Roehle, H. and Limaie, S. M., 2014, Estimation of Biomass and Carbon Storage of Tree Plantations In Northern Iran. *Journal of Forest Science*, Vol. 60(9), 363-371.
- Owers, C. J., Rogers, K. and Woodroffe, C. D., 2018, Terrestrial Laser Scanning to Quantify Above-Ground Biomass of Structurally Complex Coastal Wetland Vegetation. *Estuarine Coastal and Shelf Science*, Vol. 204, 164-176. doi:10.1016/j.ecss.2018.02.027.
- Parr, J., Pukotcharnseen, T. and La-Orphanphol, T., 2012, Bang Pu: Thailand's First Urban Nature Education Centre. *At. Hist. Bull. Siam. Soc.*, Vol. 58, 7-17.
- Patil, V., Singh, A., Naik, N. and Unnikrishnan, S., 2014, Estimation of Carbon Stocks in Avicennia Marina Stand Using Allometry, CHN Analysis, and GIS Methods. *Wetlands*, Vol. 34(2), 379-391. doi:10.1007/s13157-013-0505-y.
- Sileshi, G. W., 2014, A Critical Review of Forest Biomass Estimation Models, Common Mistakes and Corrective Measures. *Forest Ecology and Management*, Vol. 329, 237-254. doi:10.1016/j.foreco.2014.06.026.
- Thu, P. M. and Populus, J., 2007, Status and Changes of Mangrove Forest in Mekong Delta: Case Study in Tra Vinh, Vietnam. *Estuarine, Coastal and Shelf Science*, Vol. 71(1-2), 98-109. doi:http://dx.doi.org/10.1016/j.ecss.2006.08.007.
- Vashum, K., 2012, Methods to Estimate Above-Ground Biomass and Carbon Stock in Natural Forests - A Review. *J Ecosyst Ecogr*, Vol. 2, 1-7, http://dx.doi.org/10.4172/2157-7625.1000116.
- Zhou, Q. Y. and Koltun, V., 2013, Dense Scene Reconstruction with Points of Interest. *ACM Trans. Graph.*, Vol. 32(4), 1-8. doi:10.1145/2461912.2461919.