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Parameterization of Aerodynamic Roughness Length and Zero Plane Displacement Over Tropical Region Using Airborne LiDAR Data

Muhammad Zulkarnain Abdul Rahman*, Faiznor Farok, Abd Wahid Rasib, Wan Hazli Wan Kadir

TropicalMAP Research Group, Department of Geoinformation, Faculty of Geoinformation and Real Estate, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

*Corresponding author: mdzulkarnain@utm.my

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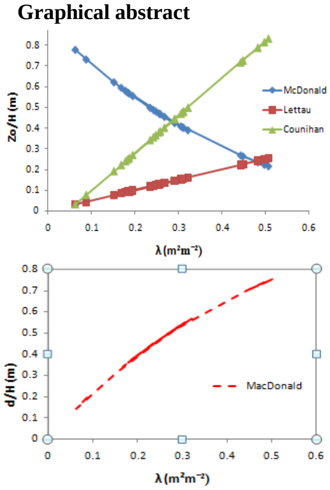
Graphical abstract



Abstract

Airborne LiDAR data has been one of the reliable data for individual tree properties estimation. High density airborne LiDAR data has been used previously for detailed reconstruction of tree geometry. The aim of this study is to estimate aerodynamic roughness over specific height (Z_o/H) and zero plane displacement (d_o) over forest area using airborne LiDAR data. The results of this study will be very useful as a main guideline for related applications to understand the role of carbon and hydrological cycles, land cover and land use change, habitat fragmentation, and biogeographical modeling. The airborne LiDAR data is first classified into ground and non-ground classes. The ground points are interpolated for digital terrain model (DTM) generation and the non-ground points are used to generate digital surface model (DSM). Canopy height model (CHM) is then generated by subtracting DTM from DSM. Individual tree delineation is carried out on the CHM and individual tree height is used together with allometric equation in estimating height to crown base (HCB) and diameter at breast height (DBH). Tree crown delineation is carried out using the Inverse Watershed segmentation approach. Crown diameter, HBC and DBH are used to estimate individual tree frontal area and the total frontal area over a specific ground surface is further calculated by subtracting the intersected crowns and trunks from the total area of tree crowns and trunks. The considered ground area i.e. plants area determined the final spatial resolution of the Z_o/H and d_o. Both parameters are calculated for different wind directions that were assumed to be originated from North/South and East/West. The results show that the estimated Z_o/H and d_o have similar pattern and values with previous studies over vegetated area.

Keywords: Airborne LiDAR; aerodynamic roughness length; zero plane displacement; forest

Abstrak

LiDAR bawaan udara data telah menjadi salah satu data yang boleh digunakan untuk anggaran sifat pokok secara individu. Tujuan kajian ini adalah untuk menentukan *aerodynamic roughness* pada ketinggian tertentu (Z_o/H) dan *zero plane displacement* (d_o) di kawasan hutan menggunakan data LiDAR bawaan udara. Hasil kajian ini amat berguna sebagai panduan utama untuk aplikasi yang berkaitan dengan peranan karbon dan kitaran hidrologi, perlindungan tanah dan perubahan gunatanah, pemecahan habitat, dan pemodelan *biogeographical*. Di peringkat awal data LiDAR bawaan udara yang dikelaskan ke dalam kelas permukaan tanah dan bukan permukaan tanah. Titik laser bagi permukaan tanah digunakan bagi menjana model rupa bumi digital (DTM) dan titik laser bagi bukan permukaan tanah digunakan bagi menghasilkan model permukaan digital (DSM). Model ketinggian kanopi (CHM) kemudiannya dijana dengan menolak DTM dari DSM. Persempadanan pokok secara individu dijalankan pada CHM dan ketinggian pokok digunakan bersama-sama dengan persamaan *allometric* bagi menganggar ketinggian asas rimbun pokok (HCB) dan diameter pada paras dada (DBH). Persempadanan rimbun pokok dijalankan menggunakan pendekatan segmentasi *Inverse Watershed*. Diameter rimbun pokok, HBC dan DBH digunakan untuk menganggar kawasan hadapan pokok individu. Sementara itu jumlah kawasan hadapan pokok di atas permukaan tanah tertentu dikira dengan menolak kawasan persilangan antara rimbun dan batang daripada jumlah keluasan rimbun pokok dan batang. Kawasan tanah ini atau kawasan menentukan resolusi ruang bagi anggaran nilai Z_o/H dan d_o. Kedua-dua parameter ini dikira pada andaian arah angin yang berbeza iaitu dari Utara/Selatan dan Timur/Barat. Hasil kajian menunjukkan bahawa anggaran Z_o/H dan d_o mempunyai corak yang sama dengan nilai-nilai yang dianggarkan dalam kajian sebelum ini di kawasan tumbuh-tumbuhan.

Kata kunci: LiDAR bawaan udara; *aerodynamic roughness length*; *zero plane displacement*; hutan

1.0 INTRODUCTION

Aerodynamic roughness length (*zo*) and zero plane displacement (*d*) of land surfaces are among essential variables for the parameterization of momentum and heat exchanges.[1,6] The experimental based method (e.g. Micrometeorological wind profile measurements) for *zo* and *d* parameterization only valid for local, in which remote sensing technology would be the reliable solution for better estimation of spatially-distributed *zo* and *d* values.[6] Recently, there have been serious efforts in developing models to estimate the exchange between the land surface and the atmosphere using passive remote sensing.[7-9] Most of these models require accurate estimation of *zo* and it is often not available. This constraint leads to a simplification in estimation *zo* by means of a simple ratio of spectral channel for example the Normalized Difference Vegetation Index (NDVI). It was noted that different methods to estimation *zo* using remote sensing over heterogeneous land surface often leads to significant errors in turbulent flux estimates.[10]

Advances in remote sensing technology, especially by Airborne Light Detection and Ranging (LiDAR) technology has allowed detailed estimation of vertical structural information of land surface. However, only few studies have utilized airborne LiDAR to parameterize *zo* and *d*. There was an early attempt, which used LiDAR to estimate *zo* based on the geometrical regularity of vegetation canopies by multiplying the ratio of the standard deviation to vegetation height in segments of a transect by the average height of the vegetation along the transect.[11] In this study, they found good agreement between *zo* estimated from airborne LiDAR with the value calculated using the Monin–Obukhov similarity theory applied to measurements of horizontal wind speed profiles. Previous study has been devoted to assess the validity of previous models (i.e. model by Choudhury and Monteith[3], Raupach[4] and Schaudt and Dickinson[12]) over cool- and warm-temperate forests in Japan[5] It was found that the results were not valid for their study area and as a consequence, they introduced a new concept in estimating *zo* and *d*. Vries *et al.*[13] utilized high density LiDAR to estimate *zo* and *d* over coppice dunes covered by honey mesquite. The results obtained using LiDAR data have a good agreement with the value measured from a vertical profile of horizontal wind speed measured at six heights. Colin and Faivre[14] estimated *zo* for a heterogeneous landscape using a combination of LiDAR and computational fluid dynamics models. They discussed the need for footprint definitions and ground measurements to validate their results. Tian *et al.*[1] used a combination of LiDAR and SPOT-5 spectral data with micrometeorological measurements to test four models to parameterize *zo* over cool-temperate forests in Heihe River basin, China. They showed that the model generated maps of *zo* from LiDAR are superior to those from satellite optical remote sensing data and suggested the use of high density LiDAR combined with source areas for eddy covariance (EC) towers to improve their validation.

Previous studies showed that estimation of *zo* and *d* basically required detailed structure of individual trees. Airborne LiDAR campaign in temperate region allows good penetration of laser pulses during leaf-off condition. In this case, vertical individual tree structure can be easily seen and suitable surface model can be used to reconstruct the three-dimensional structure of the whole trees. On the other hand, utilization of airborne LiDAR data in tropical region is limited by the fact that high density vegetation canopy will result poor penetration of laser pulses and the point clouds could only represent the top or canopy characteristics of vegetation. Density of point clouds, its accuracy (horizontal and vertical), and penetration over vegetation canopy can be determined by the LiDAR system and its position and orientation system (POS).[15] It can be concluded that the performance of LiDAR and other remotely sensed data for *zo* and *d* parameterization in tropical region still require thorough investigation especially on LiDAR system configuration and its relation to extract required parameter over different terrain conditions.

2.0 MATERIALS AND METHOD

The methodology is divided into four main phases which are pre-processing of airborne LiDAR data, estimation of individual tree attributes, estimation of aerodynamic roughness length (*zo*) and zero plane displacement (*d*), and comparison between estimated values and previous studies by other researchers (Figure 1). The first stage focuses on filtering the point clouds to distinguish ground and non-ground laser points, constructing digital terrain model (DTM), digital surface model (DSM) and canopy height model (CHM). The second stage devoted for estimation of individual tree attributes based on the delineated trees and allometric equations. Estimation of *zo* and *d* are based on the estimated individual tree geometrical properties and available models developed by previous studies. Finally the estimated values will be compared with the values obtained by previous researches.

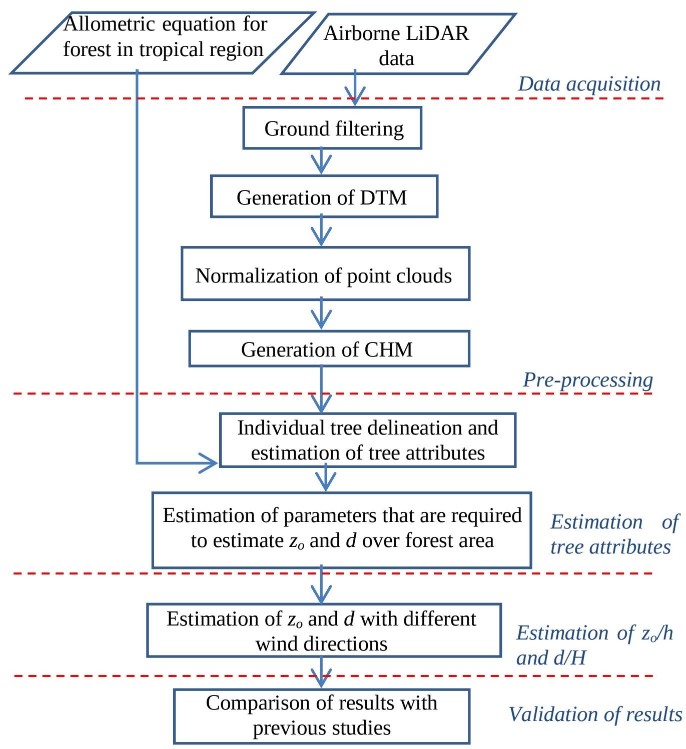


Figure 1 Flow chart of methodology

2.1 Description of data and study area

The study area is located at the Hutan Rekreasi Melaka, Malaysia (Figure 2). The area has become the recreational park since 17th April 1984. It is 359 hectares in area which consist of tall hardwood tropical trees forest and residential areas. There are nearly 10 species of trees in Air Keroh Recreational Forest. Among them are Karas (Aquilaria malaccensis) Kekatong (Cynometra malaccensis) Kempas (Kompassia malaccensis)

Kedondong Kijai (Triomma malaccensis) Yellow Jackfruit Nyatoh (Pouteria malaccensis) Malacca tree (Phylanthus embilica) Sesenduk (Endospermum malaccensis) Gwosi (Amoora malaccensis). The trees height here is range from 8 meters up to 60 meters.

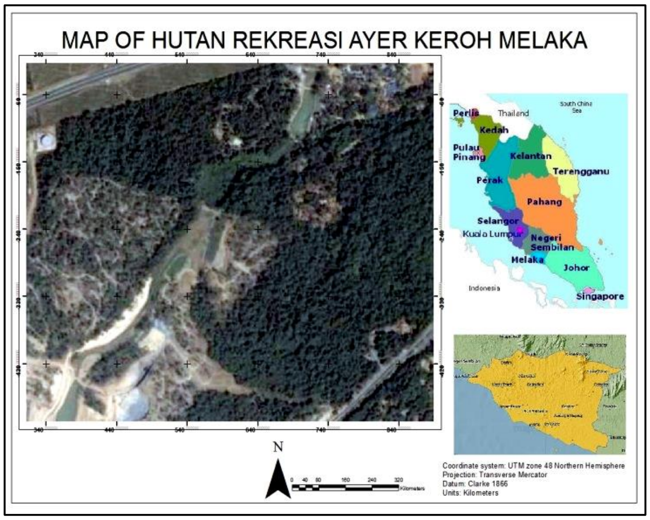


Figure 2 Hutan Rekreasi Ayer Keroh, Melaka

The airborne LiDAR data was captured by the Optech ALTM system in 2009 with average point spacing of 0.66 m

2.2 Pre-processing of airborne LiDAR data

The pre-processing of airborne LiDAR data involves filtering of original point clouds to separate ground and non-ground point clouds, generation of digital terrain model (DTM), normalization of point clouds and generation of canopy height model (CHM). The filtering process is based on the progressive morphological (PM) approach.[16] The original point clouds were normalized by subtracting the value of corresponding DTM from the elevation value of each point cloud. The normalized point clouds were used to generate CHM with a spatial resolution of 1.0 m.

2.3 Estimation of individual tree attributes

The estimation of individual tree attributes begins with individual tree crown delineation based on the CHM surface. The tree crown delineation process was carried out based on the inverse watershed (IW) segmentation approach.[17] This approach assumes that individual tree crown can be delineated by applying the inverse method of watershed segmentation from the highest point of a tree to the lowest point of a tree crown that marks the edge of crown. The individual tree crown segments are used together with a specific allometric equation for individual tree attributes estimation i.e. tree height (H), crown width (CW), crown depth (CD) and diameter at breast height (DBH).

Individual tree DBH was estimated based on the allometric equation (Equation 1) that relates DBH and maximum tree height.[18] Individual tree crown width is calculated by simplifying crown diameter measurement from the tree crown segments Equation 2.[19] Tree crown depth is calculated using Equation 3.[19]

$$DBH = \frac{H*H_{max}}{(2*H_{max})-(2*H)} \quad (1)$$

$$CW = 0.47 * H \quad (2)$$

$$CD = 0.11 * H^{1.5} \quad (3)$$

where H_{max} is the maximum height of tree with a forest stand and was set to 47 m.

2.4 Estimation of Aerodynamic Roughness Length (*zo/h*) and Zero Plane Displacement (*d/h*)

Estimation of aerodynamic roughness (z_o/H) was carried out using three models i.e. Lettau (Equation 4)[20], Counihan (Equation 5)[21] and McDonald (Equation 6).[22] Zero plane displacement (d/H) is calculated using Equation 7.[22]

$$Z_o/H = 0.5 * \lambda_f \quad (4)$$

$$Z_o/H = 1.8 * \lambda_f - 0.08 \quad (5)$$

$$Z_o/H = \left(1 - \frac{d}{H_r}\right) e^{\left(\frac{-0.5*\beta C_D}{\kappa^2}\right)\left(1-\left(\left(d/H_r\right)\lambda_f\right)^{-0.5}\right)} \quad (6)$$

$$d/H = 1 + K^{-\lambda_p}(\lambda_p - 1) \quad (7)$$

where λ_f is the frontal area index, β is coefficient to best fit the relation with experiments, C_D is the drag coefficient and κ is the Von Karman constant approximately taken as 0.4.

The frontal area index for a tree is calculated using Equation 8.

$$\lambda_f = \frac{A_f}{A_T} \quad (8)$$

where A_f is the frontal area and A_T is the total area covered by roughness element which determines the spatial resolution of the final map. In this study, the total frontal area over covered by several trees is calculated by combining the estimated crown and trunk area of individual trees (Equation 9).

$$A_f = \left(\sum_{i=1}^{n} T_i + C_i\right) - (T_{int} + C_{int} + TC_{int}) \quad (9)$$

where T_i is the area of trunk (DBH*(H-CD)) for i tree, n is the total number of tree per unit area, C_i is the crown area, T_{int} is the intersected area between tree trunks, C_{int} is the intersected area between tree crowns and TC_{int} is the intersected area between tree crowns and trunks. The A_f is calculated for two different possible wind directions i.e. 0 and 90 degrees from North. Both z_o/H and d/H were estimated with 50 m and 100 m spatial resolutions.

3.0 RESULTS AND DISCUSSION

The individual tree crown delineation process has generated about 454 individual tree segments from which individual tree attributes are estimated as described in section 2.3 (Figure 3).

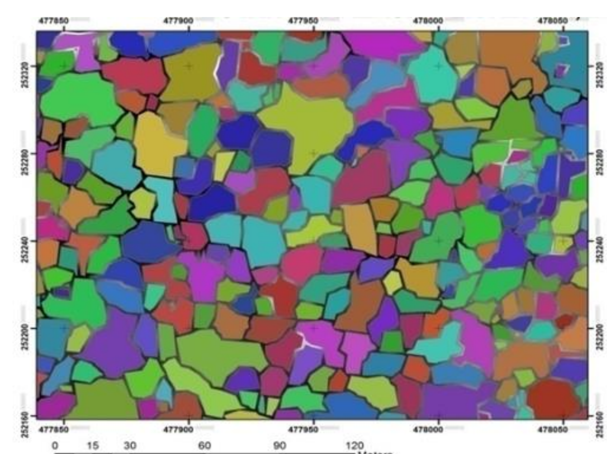


Figure 3 Individual tree crown marked by different colors of segments

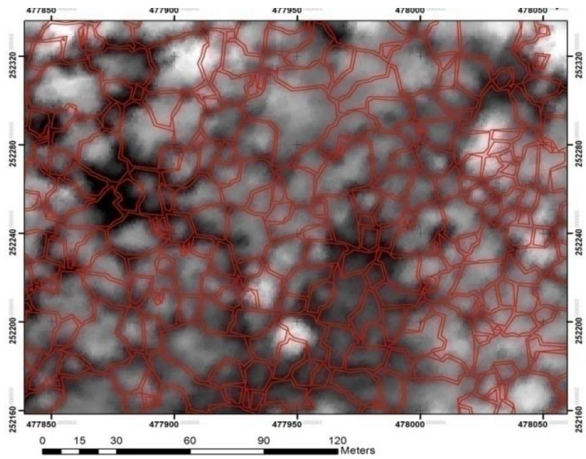


Figure 4 Individual tree crown marked by red segments overlaid on CHM

The estimations of z_o/H and d/H as described in section 2.4 were done semi-automatically based on several tools available in geographical information system (GIS). Figure 5 to Figure 8 show the example of the two-dimensional side-view of 0º and 90 º from the north for 50 m and 100 m spatial resolutions forest area. In this case, we assume that the wind flow direction will hit the first facet of the tree arrays and could not reach the second facets that were blocked by the first frontal facet. Thus, only the frontal area of the first facet will be calculated by excluding the blocking areas.

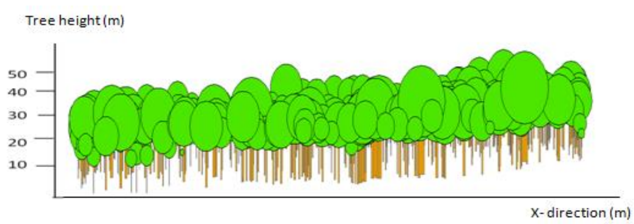


Figure 5 Two-dimensional side-view of individual tree with the assumed wind direction 0º from north (the total area, A_T is 50 m)

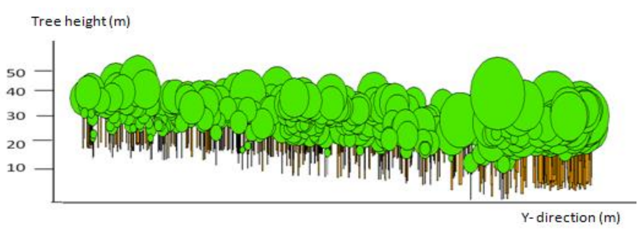


Figure 6 Two-dimensional side-view of individual tree with the assumed wind direction 90º from north (the total area, A_T is 50 m)

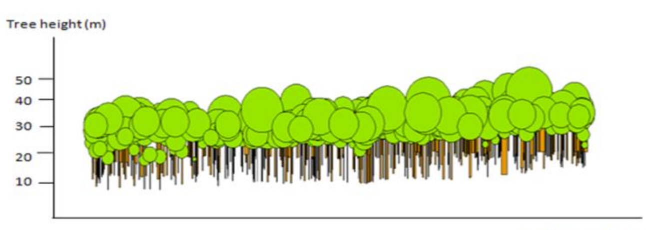


Figure 7 Two-dimensional side-view of individual tree with the assumed wind direction 0º from north (the total area, A_T is 100 m)

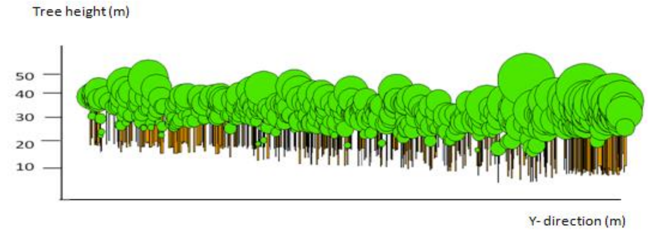


Figure 8 Two-dimensional side-view of individual tree with the assumed wind direction 90º from north (the total area, A_T is 100 m)

Lettau's z_o/H values range between 0.03 m and 0.30 m (Figure 9). This range falls in the terrain category with almost flat terrain to relatively covered by dense vegetation (high crops and scatted obstacles) as described in Table 1.

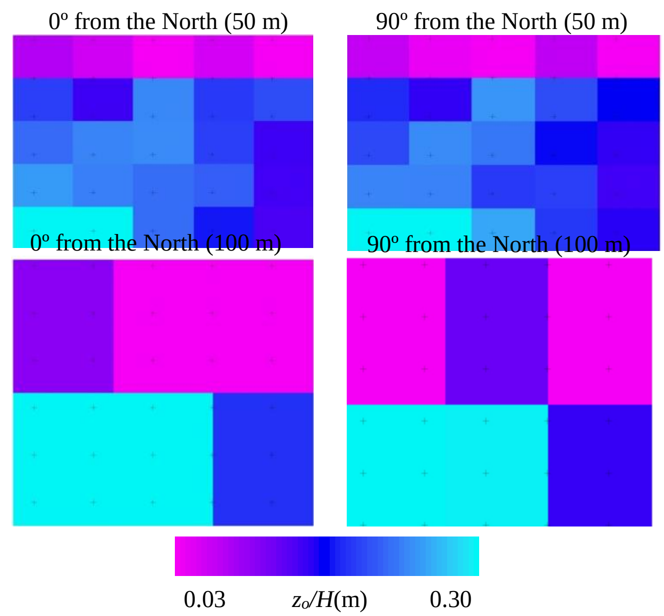


Figure 9 Spatially distributed z_o/H value with assumed wind directions 0º and 90º from north calculated using Lettau's model (the total area, A_T are 50 m and 100 m)

Table 1 Aerodynamic roughness length with its corresponding earth landscape. [23]

Surface	Landscape description	z_o (m)
Sea	Open sea, fetch at least 5km	0.0002
Smooth	Mud flats, snow, little vegetation, no obstacles	0.005
Open	Flat terrain: grass few isolate obstacles	0.03
Roughly Open	Low crops: occasional large obstacles	0.1
Rough	High Crops: scattered obstacles	0.25
Very Rough	Orchards, bushes: numerous obstacle	0.5
Closed	Regular large obstacle coverage (suburban area)	1.0
Chaotic	City centre with high and low rise building	>2

z_o/H values obtained using Counihan's model have larger ranges of value as compared to Lettau's model (Figure 10). The maximum z_o/H value reaches to the surface category with relatively regular large obstacle roughness elements. Figure 11 shows the z_o/H values obtained from the MacDonald's model that is somehow different in its distribution pattern throughout the study area as compared to Lettau's and Counihan's models. The results show that Counihan's and MacDonald's models are more sensitive to the changes in the spatial resolution (A_T). The z_o/H and d/H values are compared to the previous findings (Figure 12 to Figure 14). It is shown that the relationship between z_o/H, d/H and λ are consistence with the values obtained by means of wind tunnel experiments and wind or turbulence measurements from anemometers on tower.

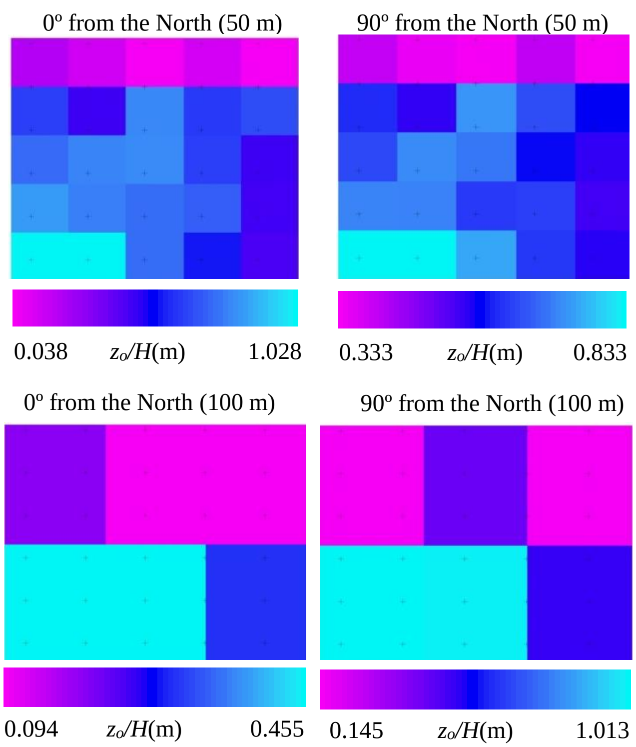


Figure 10 Spatially distributed z_o/H value with assumed wind directions 0º and 90º from north calculated using Counihan's model (the total area, A_T are 50 m and 100 m)

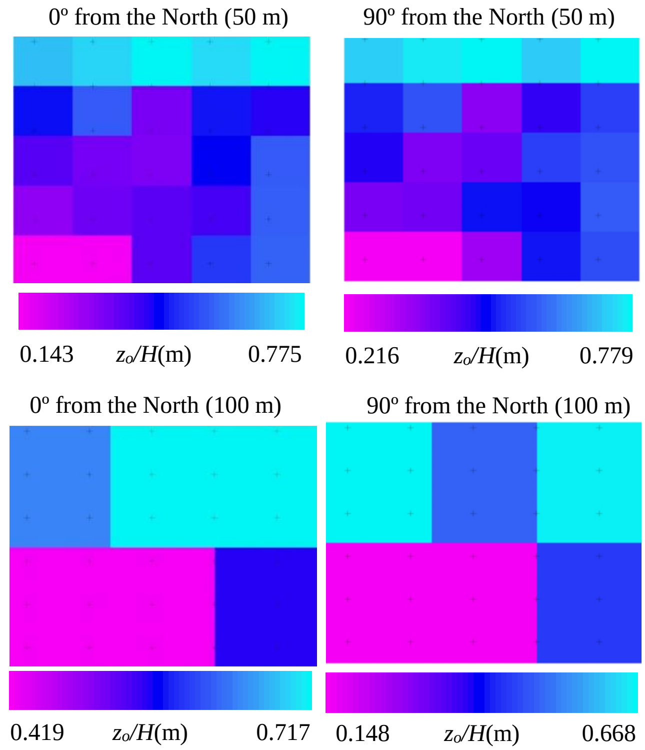


Figure 11 Spatially distributed z_o/H value with assumed wind directions 0º and 90º from north calculated using MacDonald's model (the total area, A_T are 50 m and 100 m)

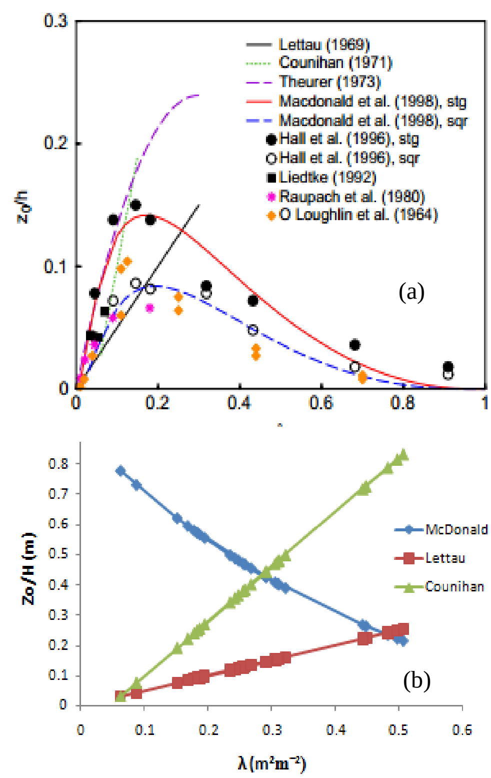


Figure 12 Comparison between z_o/H values obtained using wind tunnel experiment (a) [24] and values obtained in this study with assumed with direction of 90º (b)

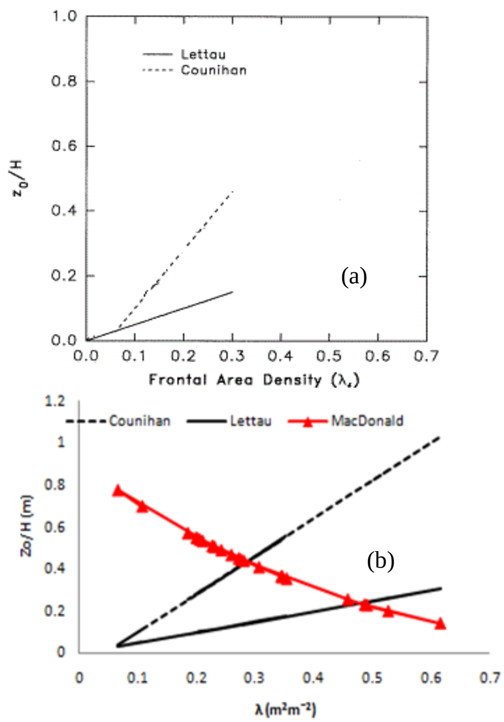


Figure 13 Comparison between z_o/H values obtained using wind or turbulence measurements from anemometers on towers (a) [22] and values obtained in this study with assumed with direction of 0º (b)

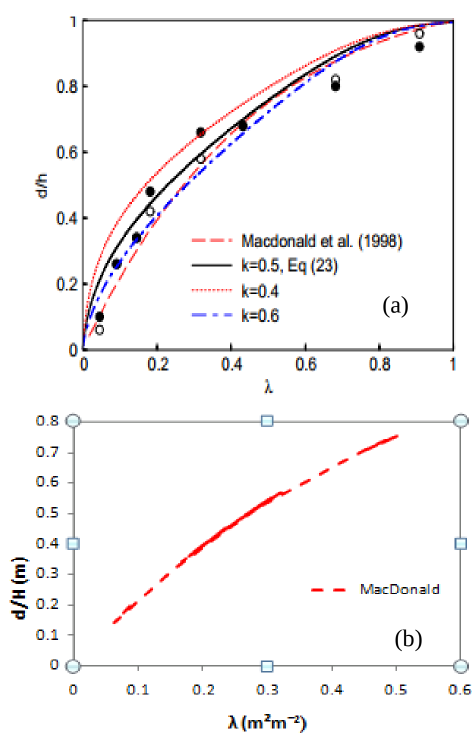


Figure 14 Comparison between *d/H* values obtained using wind tunnel experiment (a) [24] and values obtained in this study with assumed with direction of 90º (b)

4.0 CONCLUSION

We have presented a method of z_o/H and *d/H* estimation based on individual tree biometrics obtained from airborne LiDAR data. The density of airborne LiDAR data obtained in this study is considerably low, which requires the use allometric equations for individual tree attribute estimation based on delineated tree crowns. The results derived in this study have the values of z_o/H and *d/H* within the recommended ranges obtained by previous studies. Nevertheless the relationship pattern between z_o/H and *d/H* with frontal area (λ) are consistent with the previous findings that were based on wind tunnel experiments and wind/turbulence measurement on tower. We have demonstrated that both values can be estimated with different spatial resolutions and different directions of wind. The results have clearly shown that by employing individual estimation of tree attributes, the z_o/H and *d/H* values can estimated at different assumed wind directions and spatial resolution depending on the requirement of specific applications. The application of such technology in tropical region is very challenging since the penetration of laser pulse over dense tropical rainforest canopy will lead to underestimation of vegetation height and other individual tree attributes. Errors in individual tree attribute estimations will inevitably lead to the error in the z_o/H and *d/H* estimation.

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