Van Hall Larenstein University of Applied Science, Velp

Extracting Forest Parameters from Unmanned Air Vehicle Photographs of the Forest Canopy in Sarawak

Marian Barz
Student International Forestry and Nature Management

Bachelor Thesis
January 2019

Commissioned by: Van Hall Larenstein, University of Applied Science, Velp, Netherlands.
Supervisor: Peter van der Meer
Client Organization: Sarawak Forestry Corporation
Contact Sarawak Forestry Corporation: Malcom Demies

SARAWAK FORESTRY CORPORATION

van hall larenstein
university of applied sciences

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Abstract

Improved remote sensing in the field of UAV (Unmanned Air Vehicle) and SFM (Structure From Motion) photography provides the potential for efficient access to forest inventory parameters. These parameters help identify the forest structure, calculate carbon stocks, support sustainable timber extraction and forest management. The aim of this study is to demonstrate extraction of forest parameters tree height, tree crown perimeter, area and forest cover from RGB (Red Green Blue color spectral) UAV canopy images of study areas in the Sarawak forest of Borneo provided by the Sarawak Forestry Corporation. Methods (models) will be developed using open-source software package Quantum GIS. A second goal is to evaluate the results of the designed methods by comparison with measured field data delivered by the Sarawak Forestry Corporation and manually digitized data from an orthomosaic per study area.

It has been concluded that for detecting tree heights, a local maximum based model was found to be the most reliable by detecting 82% of the treetops. The extracted treetops and their corresponding heights were 86% accurate.

For tree crown shape detection, a contour based model that combines tree crown perimeter and area proved the most successful. With 78% of the tree crowns perimeters success full detected and an accuracy of 76%. The same model also managed to detect 75% of the tree crown areas and 82% accuracy.

Forest cover detection was tested with a grid based model and was found to be 97% accurate compared to the measured field data.

Further studies should investigate in improving the designed models towards higher success rate and more accurate results. As well as make them adapt to other forest types that are different than the Sarawak data set forest type. For further UAV supported forest inventories it is advisable to consider investing in LIDAR sensors for more detailed point clouds and 3D mapping of the forest canopy. Additional sensors open the possibilities to more advanced detection tools with the option to obtain additional and more accurate forest parameters.

Preface

This paper was written as a fourth year bachelor's thesis for the Forestry and Nature Management program at Van Hall Larenstein, University of Applied Sciences, Velp, and was commissioned by the Sarawak Forestry Corporation, Malaysia. My personal goals were to explore remote sensing options, to become familiar with drone acquired data sets, as well as to further develop my skills within GIS (Geographic Information System). I achieved my personal goals better than my original expectations. Remote sensing techniques as well as analyzing data sets has caught my enthusiastic interest for the future.

I would like to thank Peter van der Meer for making this thesis possible and for facilitating the contact and connection with the Sarawak Forestry Corporation. I also want to thank Dr. Malcom Anak Demies, environment manager at Sarawak Forestry Corporation for making the drone image data and field data available for this study. Dr. Alias Mohd Sood from University Putra Malaysia, department of forest production and his student Izam for answering my technical GIS related questions. I am very grateful for the help of Jack Schoenmakers from the Van Hall Larenstein University who was coming up with ideas during the development of the modules, as well as Nils Beajon, former educational assistant at the Van Hall Larenstein who was in the field collecting the measurement data. He transferred the databases for this study and provided a wide range of knowledge of drone image data processing. I also like to thank, Jamy van der Veen, a fourth year international Forestry and Nature Management student for making his drone flight data available for this study that was used for testing. A special thanks to my partner, Brittany Beagle who supported me during the whole process and also helped to manually digitizing the data. A big thank you to Andre Mucs, Erik Versluis, and Mark Grundlang for proofreading and providing feedback during the thesis writing phase. Last but not least thank you to my family and friends who offered comprehension and moral support during the entire process.

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List of Abbreviations

CHM	Canopy Height Model
DBH	Diameter at Breast Height
DEM	Digital Elevation Model
DSM	Digital Surface Model
GIS	Geographic Information System
GPS	Geographic Positioning System
GTP	Ground Truth Points
ITC	Individual Tree Crown
LIDAR	Light Detection And Ranging
M	Model
MDT	Manually Digitized Trees
RGB	Red, Green, Blue Spectral Colors
RQ	Research Question
RS	Remote Sensing
SFC	Sarawak Forestry Corporation
SFM	Structure From Motion
TCSDM	Tree Canopy Shape Detection Model
THM	Tree Height Model
THDM	Tree Height Detection Model
UAV	Unmanned Air Vehicle

1. Introduction

Tropical rainforests are the most biodiverse terrestrial habitats on earth that provide many commodities and tradable goods (Jaboury Ghazoul, 2010). However, for several decades tropical forests have been threatened by forest degradation and deforestation. In the last 25 years global tropical forest cover has declined by 35% (Tian et al., 2015). Logging activities and conversion of the forest to agricultural plantations are responsible for a substantial loss of ecosystem services including natural water storage, soil preservation and climate regulation. Global logging and burning of the tropical forests account for roughly 18% of the human caused emitted greenhouse gases (Federici, Tubiello, Salvatore, Jacobs, & Schmidhuber, 2015).

According to the FAO (Food and Agriculture Organization), Borneo has the largest area of intact tropical forest ecosystems in Southeast Asia with a forest cover up to 60% ("FAO," 2007). Nonetheless, Borneo also has a history of heavy deforestation, forest degradation and habitat loss (Bryan et al., 2013). The main reason for this is the global high demand for palm oil that results in a high conversion rate of forest to agricultural land. More pressure is then exerted on remaining forests which emphasizes the importance of sustainable forest management in order to conserve these habitats for the future (D'Annunzio, Sandker, Finegold, & Min, 2015).

In Sarawak, which is one of the regions of Malaysia on Borneo, all forest land is classified by law as permanent forest estate. This means the forest land is totally protected communal forests areas and state land forests. Forest areas that are classified as such by the forestry department Sarawak must remain forest areas in the future. However, within these laws there is room for commercial timber extraction and permissions for local residences to harvest forest goods for domestic use (Wright, 2009).

Sustainable timber extraction can also provide an economic basis for forest management and supporting habitat conservation efforts (MacDicken et al., 2015). Therefore, carefully selected logging sites according to guidelines like minimum impact logging are important assets to help finance conservation efforts. Growth, regeneration rate, ecosystem resilience and increments of these forest areas are key information factors that determine if logging can be done sustainably. Carbon stock estimations through forest inventories is another way to create revenue through carbon emission compensation programs (Kindermann et al., 2008). Inventorying the carbon stocks within an area gives an expressible value that can be considered in management strategies (Goslee et al., 2016).

Forest inventory is commonly used to gain information through forest parameters and features about the quality and condition of the forest. Conventional forest inventories have mostly been carried out by physically measuring and identifying trees in sample plots and then projecting these results into a larger area (Brown, Gillespie, & Lugo, 1989). Possible forest parameters are forest and tree characteristics such as DBH (Diameter on Breast Height), tree heights, tree crown area, above ground biomass, diversity, percentage of dead wood and forest gaps. These characteristics and parameters offer information that assist forest monitoring and allows for management adoptions.

Forestry activities are often located in remote locations and cover a large surface area; therefore using remote sensing techniques combined with UAV's (Unmanned Air Vehicle) to detect forest parameters is an obvious means of monitoring. It is more efficient in uneven terrain and can be carried out faster. Remote sensing techniques can track biological phenomena's, land use change and land cover mapping; they can track deforestation, calculate forest revenues, plan forest harvest activities, and predict weather and temperature fluctuations (Saatchi, 1996). These features can be obtained through different surveying techniques like SFM (Structure From Motion) photography, LIDAR (Light Detection and Ranging of Laser Imaging Detection and Ranging), radar and spectroscopy or magnetic resonance. The use of photogrammetric airplane, satellite and drone images is becoming more prominent and the technology is advancing (Vosselman & Dijkman, 2001).

Image processing software has been improved along with the quality and precision of recordings by UAV's. From recorded forest data from UAV's it is possible to identify single trees to extract measurements like: height, tree crown shape and DBH (Diameter on Breast Height) (Tan, Fang, Xiao, Zhao, & Quan, 2008). However, this can only be achieved with specific cameras and sensors and under ideal conditions in a forest that is not that dense. Handling the data and extracting the right features offers space for improvement and could contribute to the benefits that UAV supported forest inventory has to offer.

The area of interest for this thesis, so called study area, is located in the Sarawak region of Malaysia that is in the Northwest on the Island of Borneo (Figure 1). Sarawak shares the island with the region Sabah of Malaysia, Kalimantan which belongs to Indonesia and the nation of Brunei which is a sovereign state. The Sarawak region has a warm subtropical climate with temperatures varying between 16°C to 32°C ("The Official Portal of the Sarawak Government," 2018).

Figure 1, The Island of Borneo in the Southeast Asian with Sarawak's Regional Boundaries

1.1. Problem Analysis

Forest inventories are expensive and work intensive especially in remote areas like the forests in the Sarawak region on Borneo. Remote sensing can help to increase forest inventory efficiency. However, the use of drones equipped with high-resolution cameras, multi-spectrum sensing or LIDAR (Light Detection And Ranging) are very costly and specifically trained personnel are needed. Also, there are no open-source high-quality satellite images available of the Sarawak forest area.

In an experimental setup drone RGB (Red Green Blue) color band images of the forest canopy have been recorded in different areas spread throughout the Sarawak region. This recorded data, together with field data in the form of manual tree inventories of the monitored areas, have been made available by the Sarawak Forestry Corporation who commissioned this research. Besides a partly transformation of the recorded images towards a canopy height model, no further image processing has been performed until now.

There is a need for completing the canopy height models and developing methods which deliver the forest parameters: height, shape and overall canopy cover from the available drone recordings. Image processing algorithms without using classification tools have the potential to be faster than spectral analysis methods and can be better automated (Maire, Fowlkes, & Malik, 2009). They can also provide higher accuracy with cloudy skies and light distortion. The methods described in the literature (Panagiotidis, Abdollahnejad, Surový, & Chiteculo, 2017), (Birdal, Avdan, & Türk, 2017) and (Kallimani, 2016) generally use licensed software ArcGIS from Esri, Ecognition Essentials by Trimble and Erdas Image by Hexagon. These programs are however very expensive. For this reason open-source software packages that are free of charge and offer the same potential will be preferred. However it is not clear how accurate the methods described in the literature mentioned above perform with the use of open-source software packages. The determination of forest parameters like tree heights, forest gaps and tree crown shapes is also conditioned by the limited spectrum delivered by the RGB (Red Green Blue) drone data images.

There also is a problem in locating the manual forest inventory field data that has been collected by the Sarawak Forestry Corporation. The reason for this is inaccurate and untraceable positioning of the field data within the study areas.

1.2. Research Objectives and Research Questions

In the context of sustainable forest management effective forest inventories are necessary. The main objective according to the problem description is:

The extraction of forest parameters from UAV (Unmanned Air Vehicle) images of the canopy of the forest in Sarawak to improve forest inventories that can complement sustainable forest management. This may be achieved by methods in the form of models that can process UAV image data into an output that represents forest parameters. To make the methods easy accessible and free of charge, open-source software packages are preferred together with easy to use methods that work efficiently.

A quality evaluation of the different methods should allow comparison of the tested methods in terms of accuracy of forest parameter extraction.

According to these objectives the following research questions have been formulated:

Research Question 1 (RQ1)*:*

How can the tree crown heights, perimeter, area and canopy cover be derived from UAV (Unmanned Air Vehicle) image data using open-source software packages?

Research Question 2 (RQ2):

How accurate are the derived forest parameters compared to manual reference data?

2. Methodology

In this chapter some further background information is given and the approaches of preprocessing the data set are described. Further approaches in order to answer Research Question 1 and methodologies to answer Research Question 2 and evaluate the outcome, are described.

The following overview summarizes the overall process and methodologies as described in chapter 2.2, chapter 2.3 and chapter 2.4:

- Multiple drone image data per study area is transformed into a tree height map. (Canopy Height Model).
- Drone image data is also transformed into a photographic overview (Orthomosaic). (With Agisoft Photoscan Pro software package).
- Processing chains (models) are designed for the desired forest parameters. (In Quantum GIS).
- The designed models are used to process the tree height maps into the desired forest parameters.
- Results will be compared with field data as with manual reference data.
- Best performing model per parameter will be selected.
- For each model the accuracy will be evaluated.

2.1. Data Set and Background Information

Drone image data of the forest canopy in the Sarawak region as provided by the Sarawak Forestry Corporation will be used for the extraction of forest parameters to improve forest inventories. The Sarawak Forestry Corporation was established by the government of Malaysia in 1995 for sustainable forest management of multiple National Parks throughout the region Sarawak on Borneo. Their main targets are collecting forest revenues, controlling timber harvesting, and reforestation projects with the aim of rehabilitation of forest ecosystems. In collaboration with universities from different countries, research on forest ecosystems, training, and educational projects are provided. Van Hall Larestein University of Applied Science in Velp, Netherlands is one of these universities and together with the Sarawak Forestry Corporation this thesis study was commissioned.

Besides the drone image data the Sarawak Forestry Corporation also provided forest inventory data that was obtained by physically measuring the trees in five study areas. These study areas were determined by Dr. A. Mohd Sood from the University Putra Malaysia, Kuala Lumpur to cover at least three forest types and three canopy openness classes (Suwano, 2017). The physical measured forest inventory data is used by the Sarawak Forestry Corporation to estimate the standing timber stock and identify the forest structure. The data set from the physical forest inventories contains DBH (Diameter at Breast Height), height, canopy openness and species information for trees with a diameter larger than 10 cm. For this study, the data collected by Sarawak Forestry Corporation forms the essential reference for all forest parameters extracted by different methods (in the form of models) from the drone image data and will be referred to as field data. The field data set is presented in Appendix 14, page 53.

Five study areas have been made available near Sibu in the region Sarawak on Borneo, Malaysia. All study areas are covered with dense dipterocarp forest and are managed by the Sarawak Forestry Corporation. The study area sizes differ from each other depending on the drone flight time and area covered by photographs that have been taken. The spatial distribution of the areas is visualized in Figure 2 and their GPS coordinates are given in Appendix 1, page 31.

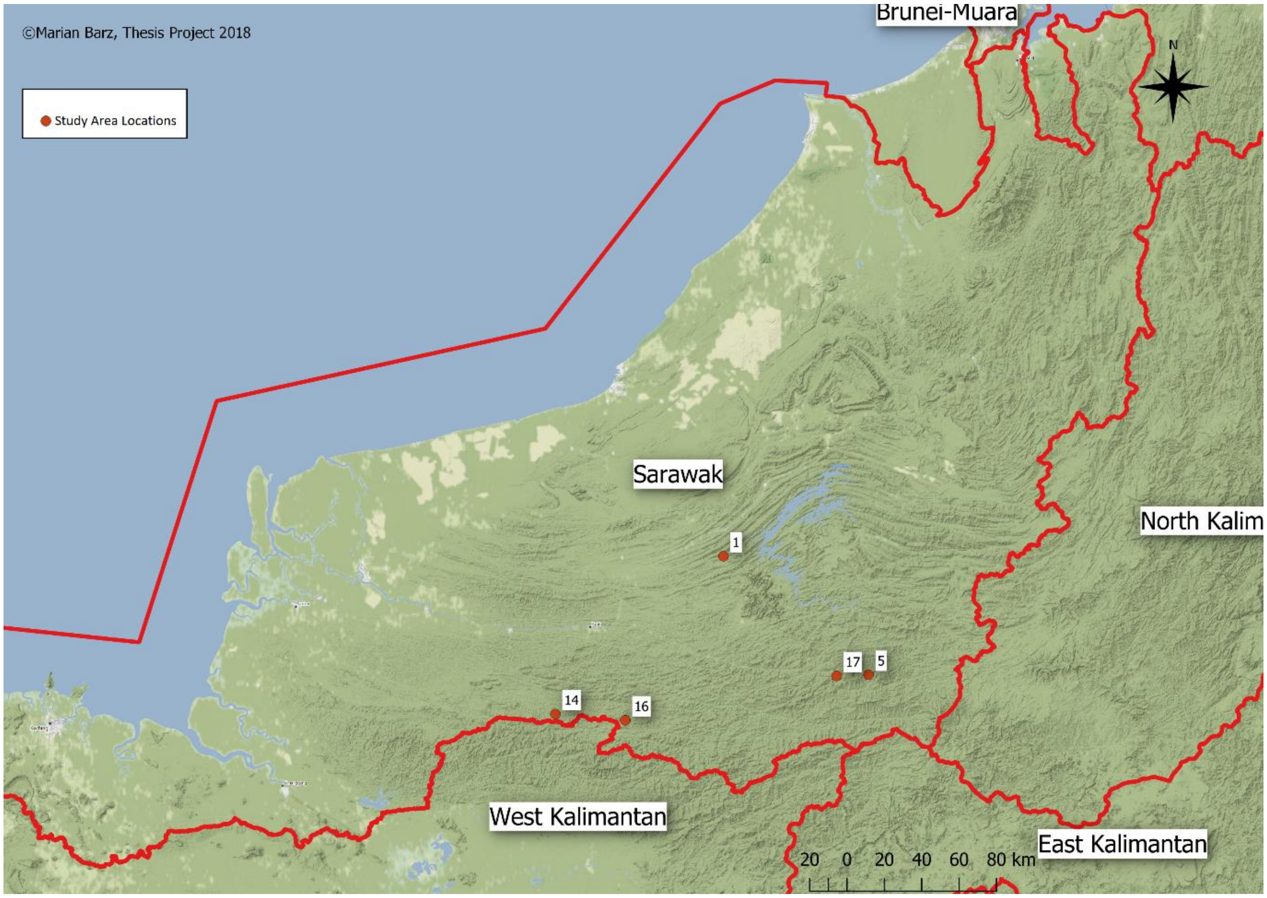

Figure 2, Study Area Locations Within Sarawak's Boundaries With All Available Study Area Locations

2.2. Preprocessing of the Data Set

In this thesis study methods in the form of models will be presented which allow the extraction of forest parameters from RGB (Red Green Blue) image data taken from the Sarawak tropical forest canopy. Models are a chain of processing algorithms that are wrapped together as one process with an input and an output. To create a usable input for the models some preprocessing needs to be performed on the drone image data. The drone image data recorded by the Sarawak Forestry Corporation were obtained through Nils Beaujon, a former student at the VHL University of Applied Science.

For each of the five study areas, between 30 to 150 drone images have been taken with GPS coordinates and flight height information imbedded. The drone images have a given overlap to allow further processing.

The drone image data has been transformed in Agisoft Photoscan Professional into a format that can be used as input for the model design. A summary of the steps that are taken is shown as a flowchart in Figure 3 and are described below:

- From the set of overlapping images a 3D point cloud is created by successive triangulation. A point cloud consists of a set of data points that have a position in a 3D space.
- From the point cloud a Orthomosaic is created (Figure 4), representing a geometrically correct collection of photographs combined (“new farmer – Medium,” n.d.). The Orthomosaic has a pixel cell size of 0.15m and will be used as visual reference for the study areas and for manually digitizing the tree crowns.
- From the point cloud a digital surface model is also created which represents the surface height inclusive trees and other objects.
- Using ground truth points a digital terrain model is created also from the point cloud which represents the terrain height without trees and objects.
- In Quantum GIS the two models, digital surface model and digital terrain model are subtracted from each other which results in the canopy height model. The canopy height model represents the height from the ground up to the canopy top. The canopy height model has a pixel cell size of 0.8m and will be used as an input for the designed models. An example of the canopy height model is given in Figure 5.
- A low pass filter is applied to filter out extreme values that could have been created by false calculations during creating the canopy height model.

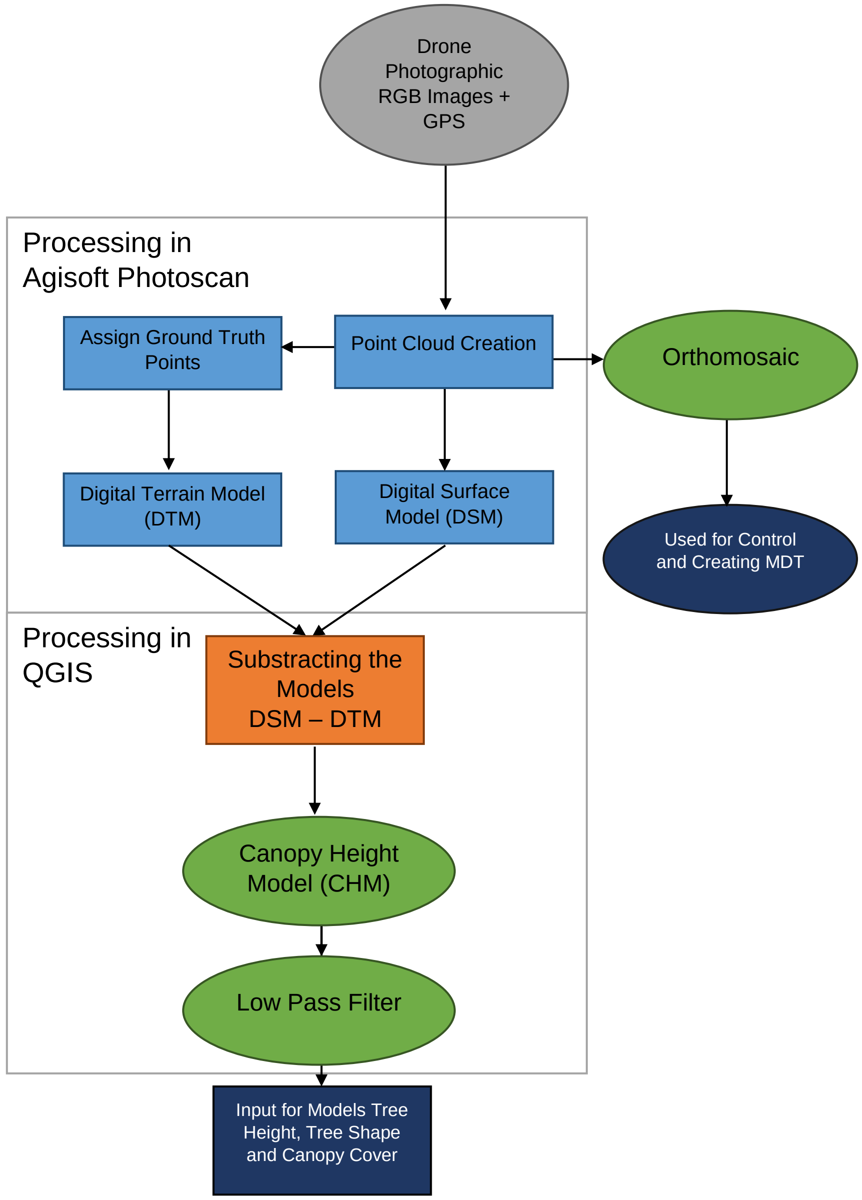

Figure 3, Flowchart of the Image Processing Procedure to Obtain the Canopy Height Model and the Orthomosaic. (MDT – Manual Digitized Trees)

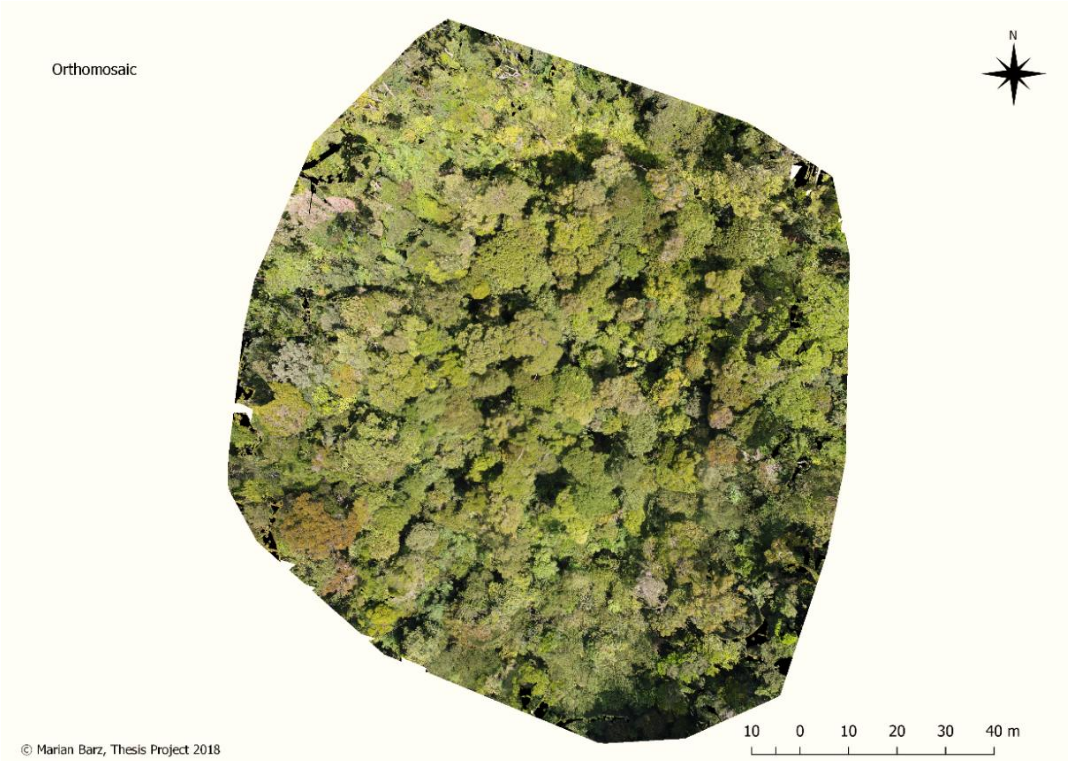

Figure 4, Example of an Orthomosaic of the Study Area 5

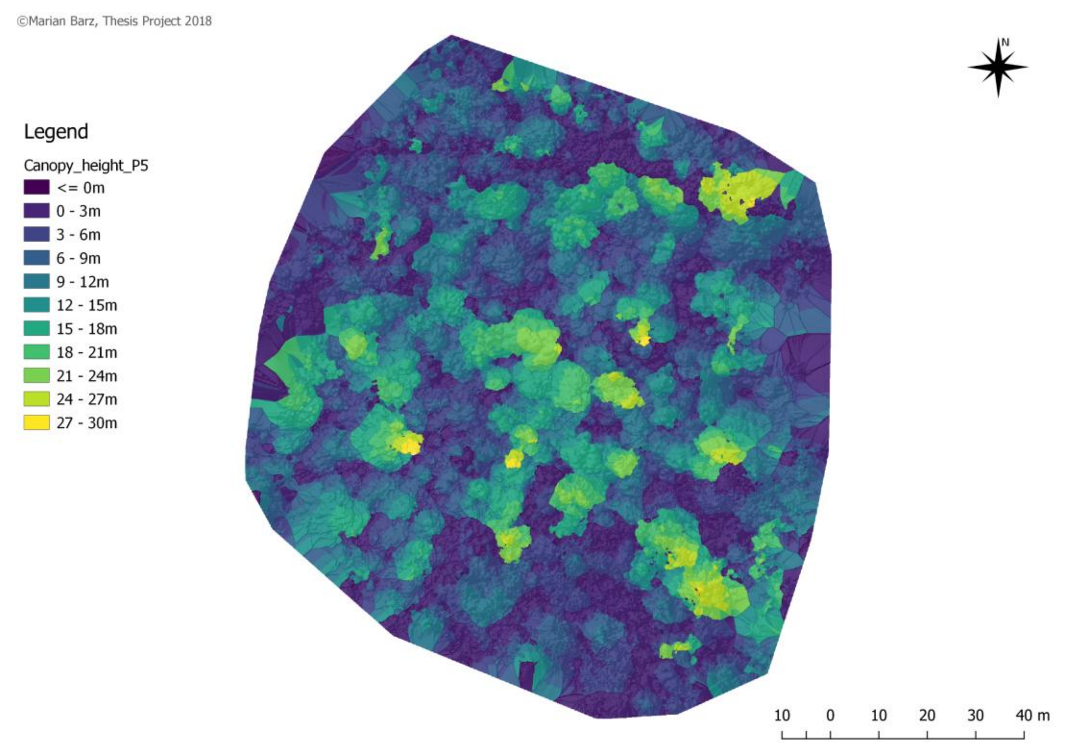

Figure 5, Example of a Canopy Height Model of the Study Area 5

2.3. Model Design Approaches

To answer Research Question 1; "*How can the tree crown heights, perimeter, area and canopy cover be derived from UAV (Unmanned Air Vehicle) image data using open-source software packages?"* different models were designed inspired by literature and research to extract forest parameters from the canopy height model. A total of 14 models were created in Quantum GIS. The models were tested and narrowed down to six after excluding obvious inaccurate or faulty models. The approaches for the six models which were tested are described below:

<u>Two Different Tree Height Detection Models:</u> *"A treetop is defined by the highest point on a tree expressed in meters"* (Blozan & President, 2008). To find this specific point within a tree crown it is important to differentiate between trees that are close together. The designed models are called Tree Height Detection Models. There will be two different approaches worked out and tested for Model 1 and Model 2.

- The first model (Model 1) is differentiating tree crowns by "contours lines" inspired by Maire et al (Maire et al., 2009), converting this process to Quantum GIS.
- The second model (Model 2) is based on the "local maxima tool" that has been described by multiple research papers to locate tree heights, one of them is Birdal et al (Birdal et al., 2017).

<u>Three Different Tree Crown Shape Detection Models:</u> *"A tree crown perimeter is the length of the circumference of a tree crown expressed in meters and the tree crown area is the section within the perimeter circumference, expressed in square meters"* (Kramer, H., & Akça, 1995). These two parameters: perimeter and area are very closely related with each other. The models however can return different results for each of the two parameter. For this reason there has been made a difference between perimeter and the area detection models results. Together these models are called tree crown shape detection Models. Three different approaches will be worked out and tested in Model 3, Model 4 and Model 5:

- In the third model (Model 3) "Delaunay triangulation" is applied which is not a common tool to be used in forestry related remote sensing techniques, but its ability to recreate segments from points offers potential that will be tested (Arbela et al., 2011).
- In the fourth model (Model 4) again "contour lines" are used to differentiate tree crowns outlines as described by Birdal, (Birdal et al., 2017).
- The fifth model (Model 5) is based on hydrology tools and virtual water flows commonly named "watershed segmentation" to identify tree segments, described by (Eysn et al., 2015), (Wallace, Wallace, Musk, & Lucieer, 2014) and (Panagiotidis et al., 2017).

<u>One Canopy Cover Detection Model:</u> *"Canopy cover represents how much of a certain area is taken up by the tree crown area expressed in percentage"* (Kleinn, 2007). The canopy cover detection model should give a close estimation of the canopy openness and cover.

- The sixth model (Model 6) to detect forest cover is based on dividing the canopy height model into a grid and then extracting the regions that are above the height that defines a canopy.

2.4. Model Evaluation Procedure

To answer Research Question 2; "*How accurate are the derived forest parameters compared to manual reference data?*" the output data of the designed models needed to be tested against reference data. However the manually collected field data by the Sarawak Forestry Corporation did not provide accurate study area location data. So, individual measured trees could not be located. As it was not possible to compare one to one locations of identified trees and model calculated trees, a statistical approach was chosen to evaluate the model qualities. The evaluation procedure is summarized as a flowchart in Figure 6.

To test how accurate the models perform the canopy height model and orthomosaic of the available study areas both were visually analyzed and distinguishable trees were digitized (Manual Digitized Trees) by following the pixel differentiations of the two images. For each study area between 20 to 60 trees were manually identified and digitized. The identified trees were assigned an unique ID code. The area, perimeter and highest point were calculated for the accuracy statistics and performance. During digitizing it was very important to select trees that are very well distinguishable by sight using the tools of canopy height model differentiation, analyzing the orthomosaic and assigning different color band settings to visualize different aspects that define a tree crown. For this specific subject Brittany Beagle, who worked for the Parks and Recreation Department for the city of Calgary and who has experience of GIS (Geographic Information System), related manually digitizing trees and tree differentiation, helped to go through the data and to identify most of the tree crowns.

The values extracted by the tree height detection models and tree crown shape detection models could then be paired with the created manual digitized tree data. To filter out unusual and extreme values the standard deviation of all models extracted values were calculated. The models that extracted standard deviation values that deviated more than the average manually digitized tree standard deviation were market as failures. The values that are not marked as failures are marked as successful detections and it is expressed as a percentage of success rate.

Accuracy represents a measure of degree of closeness between two different values expressed in percentage. In this study the accuracy of the designed models extracted values in relation to their manual values is calculated according to the following formula:

<u>Accuracy % = 100 – ((Manual Digitized Tree Values – Model Values) / Manual Digitized Ttree Values x 100)</u>

To visualize the statistical relation between the manual and the model data both pair values were inserted into a scatter plot with a trend line. The slope of the trend line, also known as correlation coefficient (r), expresses how strong the relation between the two pair variables is. When r = 1 or r = -1, this indicates that there is a very strong positive or negative correlation.

A good model should have a minimum positive or negative correlation coefficient of r = 0.5 between the models extracted parameter values and its comparable manual values. r = 0.5 represents a moderate correlation.

The field data was used to compare the overall average height values extracted by the tree height detection models per study area. In the same way the average canopy cover data of the field data was compared with the average of the extracted values by the canopy cover detection model. The field data could not be used for comparing tree crown shapes since this parameter information was not available in the field data.

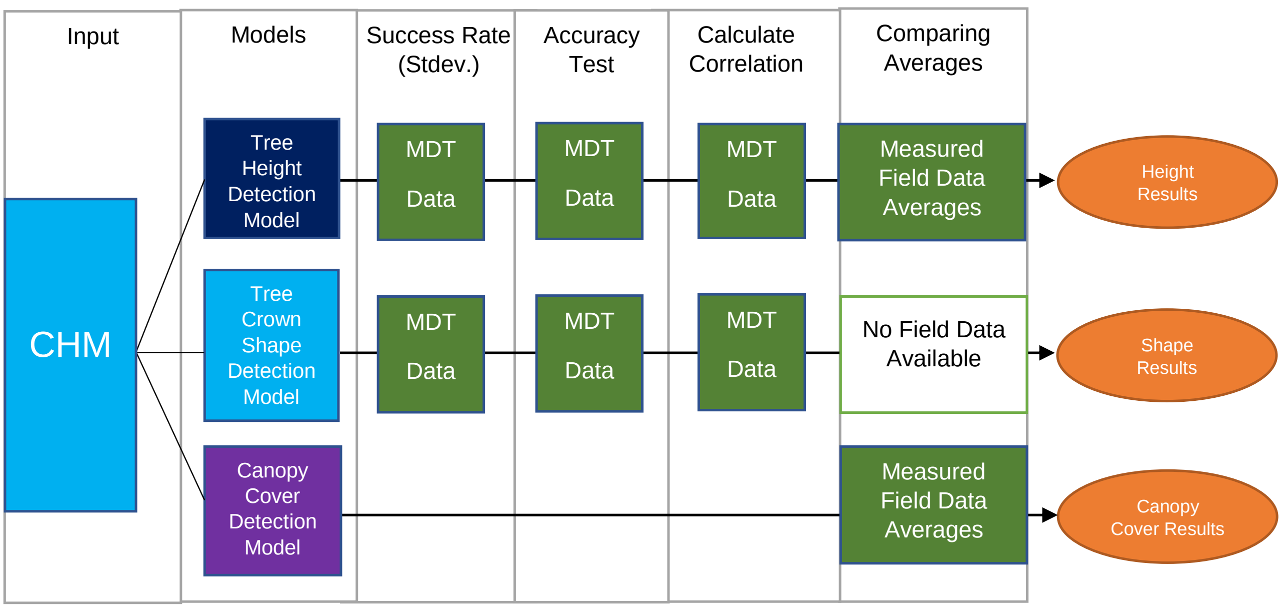

Figure 6, Chart of the Models Evaluation Procedures Comparing them With MDT (Manual Digitized Tree) Data and Measured Field Inventory Data With the CHM (Canopy Height Model) as Input.

3. Results

An overview of all six model results gives an insight how model tree heights, perimeter, area and canopy cover can be derived from UAV image data using open-source software packages, as stated in Research Question 1. The best performing models are marked green and the poor performing are marked red. This is done to seek out how accurate the derived forest parameters are compared to their manual reference data as stated in Research Question 2. A complete overview of the results is listed in the tables below (Table 1, Table 2, Table 3, Table 4). Further on in this chapter the results per achieved parameter will be explained.

Table 1, Tree Height Detection Models Results Overview

Results:	Success Rate	Accuracy	Correlation
Model 1	68%	67%	0.74
Model 2	82%	84%	0.78

Table 2, Tree Crown Perimeter Detection Models Results Overview

Results:	Success Rate	Accuracy	Correlation
Model 3	77%	37%	0.20
Model 4	78%	76%	0.80
Model 5	58%	64%	0.57

Table 3, Tree Crown Area Detection Models Results Overview

Results:	Success Rate	Accuracy	Correlation
Model 3	76%	31%	0.41
Model 4	75%	82%	0.68
Model 5	63%	64%	0.70

Table 4, Canopy Cover Detection Model Results Overview

Results:	Accuracy
Model 6	97%

(The results are color highlighted according to performance, green; best performance, orange; moderate performance, red; worst performance)

3.1. Tree Height Detection Models

In a dense forest, tree crowns tend to grow into one another; this makes it difficult to differentiate between each other. Furthermore, a single tree can have multiple crown peaks that can be identified as two different trees. In order to reduce these biases two models were developed, tested and the results were compared. A short description of the tree height detection models is given:

Model 1 is based on differentiating tree crowns by contour lines of the canopy height model and calculating the highest point within these contours. A more detailed description of Model 1 together with a workflow and example of its output layer is presented in Appendix 4, page 34.

Model 2 is based on the local maxima tool in Quantum GIS to find the treetop within an area. A more detailed description of Model 2 together with a workflow and example of its output layer is presented in Appendix 5, page 36.

3.1.1. Treetop Height Detection Performance (Model 1, Model 2)

The tree heights extracted by the models were compared with the manual digitized tree values and the field measured data. To determine the success rate of the models, the standard deviations of the models and the manual digitized trees were calculated.

In Model 1 the average standard deviation of the extracted values is $\sigma = 2.78$ which results in 149 out of 219 successful detections and thus a success rate of 68%. Model 2 had 176 successful detections out of 215 which accounts to 82% successful treetop detections (Appendix 10, page 45).

After filtering out the unsuccessful detections, the accuracy of the remaining values is calculated by determining the difference between the manual digitized tree heights and the models results. The remaining pairs are calculated to be 67% accurate for Model 1 and 84% for Model 2 (Table 5).

This means that the values extracted by Model 2 are closer to their paired manual values than Model 1. Both Model 1 and Model 2 show a very strong positive correlation to their manual pairs with both close to identical curves. Also, their correlation coefficients are both high, $r = 0.97$ for Model 1 and $r = 0.99$ for Model 2, as shown in Figure 7 and Figure 8.

Since Model 2 did perform with a higher success rate and accuracy than Model 1 on the manual digitized tree data, its findings were compared with the field measured data that was provided by the Sarawak Forestry Corporation. The averages, accuracy and standard deviations were calculated. The average height value of Model 2 was lower than Model 1 with a difference of 2.34 meters which resulted in 87% accuracy of Model 2 (Table 6). The data that was used for comparison is presented in: Appendix 11, page 46; Appendix 12, page 46; Appendix 13, page 50; Appendix 18, page 62.

Table 5, Accuracy Test for Height Detection of Model 1 and Model 2

Study Area ID	Model 1	Model 2
1	75%	85%
5	60%	68%
14	74%	82%
16	70%	86%
17	57%	98%
Total per Model:	67%	84%

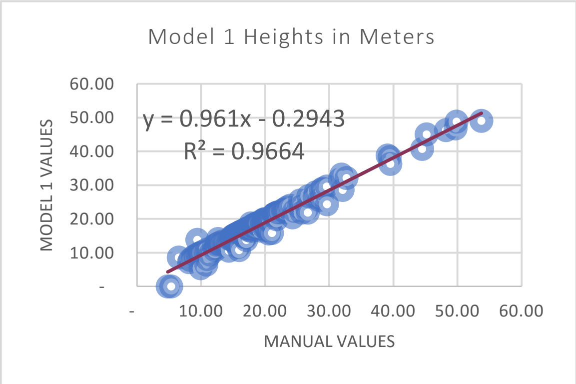

Figure 7, Correlation Between the Manually Digitized Tree Height's and Model 1 Calculated Height's

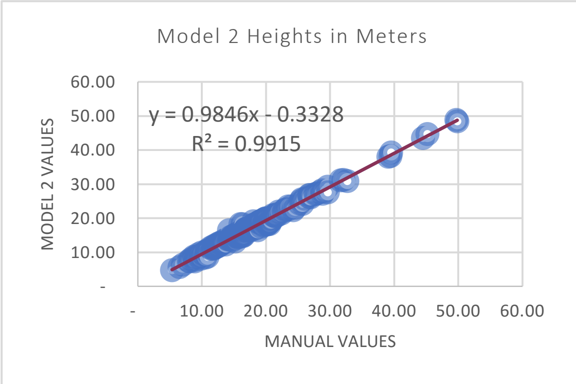

Figure 8, Correlation Between the Manually Digitized Tree Height's and Model 2 Calculated Height's

Table 6, Comparing Sarawak Forestry Corporation Measured Average Height Data with Model 2 Calculated Height Data

Study Area ID	SFC Average	Model 2 Average	Accuracy Average
1	18.26	26.48	69%
5	19.86	12.69	64%
14	19.02	13.18	69%
16	17.09	12.07	71%
17	19.02	17.14	90%
	18.65	16.31	87%

3.1.2. Interpretation of the Tree Height Detection Model Results

Model 1 performed with a success rate of 68% and an accuracy rate of 67%. This model uses the fixed distance buffer tool in Quantum GIS that groups multiple points of a treetop together (for detailed description of Model 1: Appendix 4, page 34). The tool uses a single fixed distance to generate the buffer; however a tree crown has variable dimensions. Thus, if the fixed distance is too high, multiple tree crows are merged together and if the fixed distance is too low then one tree crown is turned into multiple treetops. Therefore, the trees that can be detected by this model are strictly dictated by the fixed distance parameter. The low success rate and accuracy of Model 1 is most likely due to the fixed distance parameter. Trees within a dense forest, like that of Sarawak, have such variable tree crown dimensions and are so close together that a fixed parameter is not able to detect all of the trees. Probably explains the low success rate and accuracy of this model. The inaccuracy and low success rate makes Model 1 qualifies it as an inefficient tool for extracting the forest parameter tree heights. However, despite this inaccuracy Model 1 would most likely perform well in open fields with only a few trees in the area.

Model 2 performed with a success rate of 82% and an accuracy rate of 84%. This model uses the local maximum tool and searches for the pixel value with the highest height; this model is based upon methods described by Colgan et al. and Davies et al (Colgan, Baldeck, Féret, & Asner, 2012), (Davies, Palmiotto, Ashton, Lee, & Lafrankie, 1998), (for detailed description of Model 2: Appendix 5, page 36). The pixel size determines the range within which the local maximum tool is looking for its maximum treetop value, therefore, model 2 is limited by the pixel size parameter that is set within the model. Changing the pixel size parameter can cause data loss, as pixel values of merged pixels are averaged together. If the pixel size parameter is set too high than the tool looks at too large range and different trees will be grouped together as one. If the range parameter is set too low than the tool looks within a too small range resulting in one tree having multiple treetops. Therefore, choosing the right parameters is critical for the model to correctly detect tree heights. The chosen parameters for this model resulted in a high accuracy and success rate on the Sarawak dataset. Compared to the other models, based on the accuracy and success rate Model 2 performed the best in detecting tree heights.

3.2. Tree Crown Shape Detection Models

The tree crown shape detection models can detect two different forest parameters, tree crown perimeter and tree crown area. Three models have been designed for extracting these parameters. The models use different approaches and deliver various results per parameter. Therefore it is possible that models can perform more accurate on the perimeter parameter than on the area parameter. A short description of the tree crown shape detection models is given:

Model 3 uses Delaunay triangulation to recreate a tree crown shape from the slightly higher slope at the edges of a tree crown. A more detailed description of Model 3 together with a workflow and example of its output map layer is presented in Appendix 6 page 37.

Model 4 makes use of contour lines of the canopy height model to determine tree crown boundaries. A more detailed description of Model 4 together with a workflow and example of its output map layer is presented in Appendix 7 page 39.

Model 5 is called the watershed segmentation approach because it uses a hydrology tool that fills inverted tree crowns virtually with water. As a result, the stagnating water basins represent individual tree segments. A more detailed description of Model 5 together with a workflow and example of its output map layer is presented in Appendix 8, page 41.

3.2.3. Tree Crown Perimeter Detection Performance (Model 3, Model 4, Model 5)

The perimeters values of the models were compared with the manual digitized tree data and the standard deviations were calculated in order to determine the rate of successful detections.

Model 3 has an average standard deviation of σ = 15.06 that resulted in 149 out of 221 success full detections and thus a success rate of 77%. Model 4 had a standard deviation of σ = 13.00 that resulted in 169 out of 217 success full detections and thus a success rate of 78%. Model 5 had a low standard deviation of σ = 10.41 that resulted in 127 out of 219 success full detections and thus an also low success rate of 58% (Detailed overview in Appendix 10, page 45).

After filtering out the unsuccessful detections the accuracy of the remaining values is calculated by determining the difference between the manual digitized tree perimeter and the models results. The accuracy was very low at 37% for Model 3 and reasonably higher on the other two models. Model 4 with 76% followed by Model 5 with 64% (Table 7).

The correlation to its manual pairs is below a weak correlation coefficient of just 0.21 (Figure 9), whereas Model 4 with a very strong 0.80 (Figure 10) followed by Model 5 with a still moderate correlation of r = 0.57 (Figure 11). The data these findings are based on is presented in: Appendix 15, page 55; Appendix 16, page 58; Appendix 17, page 59.

Table 7, Accuracy Test for Perimeter Detection Models

Study Area ID	Model 3	Model 4	Model 5
1	38%	85%	66%
5	21%	69%	69%
14	53%	76%	66%
16	18%	82%	66%
17	53%	69%	54%
Total per Model	**37%**	**76%**	**64%**

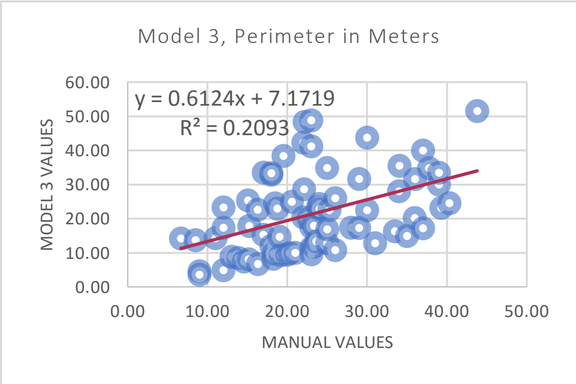

Figure 9, Correlation Between the Manually Digitized Tree Perimeter's and Model 3 Calculated Perimeter's

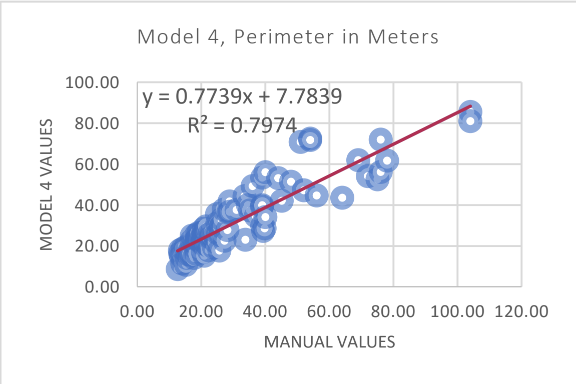

Figure 10, Correlation Between the Manually Digitized Tree Perimeter's and Model 4 Calculated Perimeter's

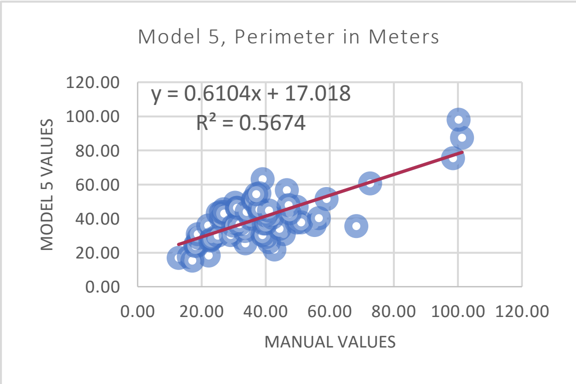

Figure 11, Correlation Between the Manually Digitized Tree Perimeter's and Model 5 Calculated Perimeter's

3.2.4. Tree Crown Area Detection Performance (Model 3, Model 4, Model 5)

The area values of the models were compared with the manual digitized tree data and the standard deviations were calculated in order to determine the rate of successful detections.

Model 3 has an average standard deviation of σ = 23.29 that resulted in 167 out of 221 success full detections and thus a success rate of 76%. Model 4 had a standard deviation of σ = 13.32 that resulted in 161 out of 217 success full detections and thus a success rate of 75%. Model 5 had a high standard deviation of σ= 21.54 that resulted in 139 out of 219 success full detections and thus an also low success rate of 63% (for a detailed overview Appendix 10, page 45).

After filtering out the unsuccessful detections the accuracy of the remaining values is calculated by determining the difference between the manual digitized tree crown area and the models results. Model 3 performed low on the accuracy test, particularly on study area 16 with only 7% accuracy that resulted in an average accuracy of just 31%. Model 4 scored 82% accuracy and Model 5, 64% (Table 8).

Model 3 showed a moderate correlation between its manual pairs with a coefficient of r = 0.64 (Figure 12). Model 4 showed a strong correlation of 0.83 (Figure 13) and Model 5 a very strong correlation of r = 0.86 (Figure 14). The data these findings are based on is presented in: Appendix 15, page 55; Appendix 16, page 58; Appendix 17, page 59.

Table 8, Accuracy Test for Area Detection Performance

Study Area ID	Model 3	Model 4	Model 5
1	22%	81%	66%
5	49%	82%	69%
14	37%	84%	66%
16	7%	84%	66%
17	41%	80%	54%
Total per Model	31%	82%	64%

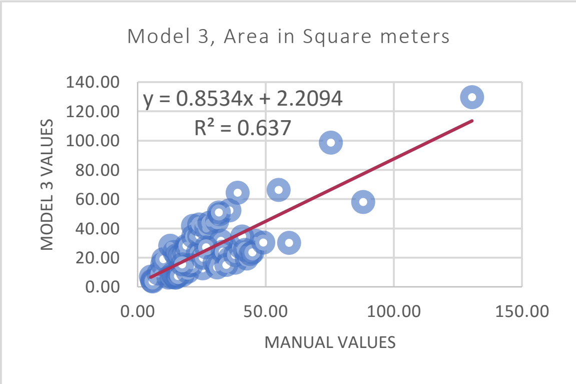

Figure 12, Correlation Between the Manually Digitized Tree Area's and Model 3 Calculated Area's

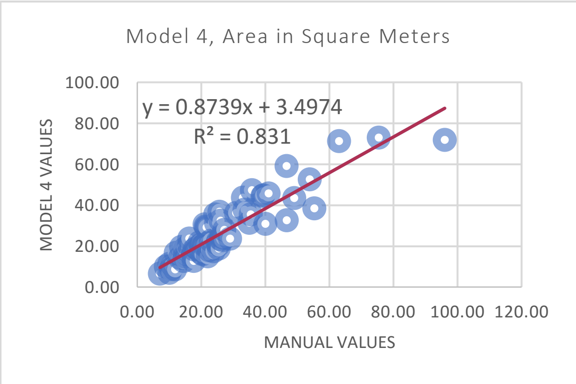

Figure 13, Correlation Between the Manually Digitized Tree Area's and Model 4 Calculated Area's

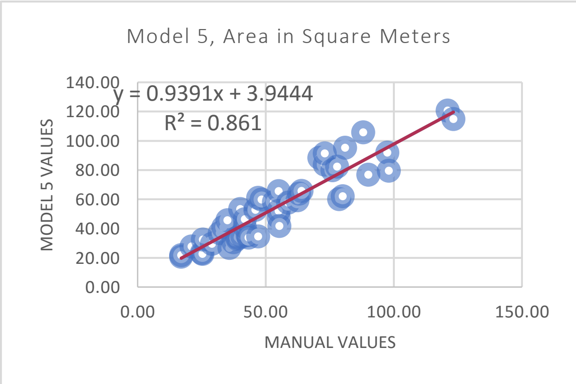

Figure 14, Correlation Between the Manually Digitized Tree Area's and Model 5 Calculated Area's

3.2.5. Interpretation of the Tree Crown Shape Detection Model Results

Model 3 performed with a very high success rate of 77% for tree perimeter detection and 76% for tree area detection. Yet, the accuracy of the model was very low; 37% for tree perimeter detection and 31% area detection. The low accuracy most likely is due to the Delaunay triangulation tool that this model makes use of. The tool creates small polygons where the slope angle of the tree crown is high and larger ones where the slope angle is low. Typically a tree crown has a higher slope near the edges, however, tree crown shapes are dynamic and higher slopes can sometimes be found further inwards of a tree crown. These higher slope polygons are filtered out together with the tree crown edge polygons resulting in warped tree crown shapes. This explains the high success rate of the model because most tree crowns are being recreated. But the low accuracy of the perimeter and area values returned by the model explains the distorted tree crown shapes. The low accuracy makes model 3 not an ideal model to use in the detection of tree crown shapes for the Sarawak dataset.

Model 4 performed the best out of all tree crown shape detection models thus it was successful and accurate in detecting tree crown perimeters. This model had a success rate of 78% in detecting the perimeter of tree crowns and a success rate of 75% in detecting the tree crown areas. The accuracy of the model was also high with a 76% accuracy rate in detecting the tree crown perimeter and 82% accuracy in detecting the tree crown area. Model 4 uses the contour tool and creates contours for every elevation difference thus the model draws a contour line for almost every tree (for detailed description of Model 4: Appendix 7, page 39), which explains the high success rate of this model. The created contours by Model 4 follow the geometry of the tree crown, as does the manual digitized trees, which resulted in high accuracy. Despite, the high accuracy and success rates of Model 4 there is one main limitation; tree crowns that are grown together will not always be differentiated with contours and they may be merged together. Still, overall this model was found to be the most successful of the three different tree crown shape detection models.

Model 5 makes use of the watershed segmentation method which is the most frequently described method by literature and offers a good potential to detect individual trees in plantation areas (for detailed description of Model 5: Appendix 8, page 41). However, the generated model performed very poor on the Sarawak data set. The model had a 58% success rate in detecting tree crown perimeters and a 63% success rate in detecting tree crown areas. A possible explanation for this poor performance is that in a dense forest, as it is found in Sarawak, there is not enough differentiation between tree heights with various tree crown sizes. Thus the results of the watershed segmentation tool in this area either detect too many small or just a few large tree crowns, neither of which result is ideal in a dynamic forest with various tree crown sizes. However, the trees that the model was able to detect were detected with an average accuracy of 64% when compared with the manual digitized tree data. Overall, this model is not ideal for detecting tree crown shapes but does offer potential in different circumstances with refined parameters.

3.3. Canopy Cover Detection Model Results

The Canopy Cover Detection Model 6 is the only designed model of its kind for this thesis study. It identifies what areas are above a given height that would determine the canopy. A more detailed description of Model 6 together with a workflow and example of its output layer is given in Appendix 9, page 43.

3.3.6. Canopy Cover Detection Performance

The average calculated canopy cover by Model 6 per study area was compared with the average field measured data from Sarawak Forestry Corporation. This resulted in 97% overall average accuracy for Model 6 extracted canopy cover (Table 9). The field data these findings are based on is presented in: Appendix 14, page 53.

Table 9, Canopy Cover Detection Model 6 Accuracy Results Compared With the Sarawak Forestry Corporations Field Measured Data

Study Area ID	SFC Measured Data	Model 6 Data	Accuracy
14	89%	89%	100%
5	90%	88%	98%
1	87%	90%	97%
16	85%	89%	95%
17	88%	92%	96%
			97%

3.3.7. Interpretation of the Canopy Cover Detection Model Results

Model 6 (Model for detecting canopy cover) was 97% accurate when comparing the results with the measured field data. This is the only model of its kind that was tested on detecting canopy cover and the results were successful. This model detects the canopy cover through a grid, detecting the occurrence of a tree or not. For a more detailed description of Model 6: Appendix 9, page 43. This model could be adapted to perform the calculations faster by increasing the grid size with a loss of accuracy as a trade off, which makes this model adaptable to any data set size and desired accuracy. Further more; Model 6 is not dependent on forest type since the tree shapes do not influence the model. Therefore, Model 6 is a highly accurate model for detecting canopy cover and can be applied to various forest types.

4. Discussion

The results of the models are strongly depending on the quality of the canopy height model. In some study areas the drone data is of lower quality, resulting in a distorted and slightly warped canopy height model. In the case of study area 16, the quality is most likely influenced by clouds that can be identified in the orthomosaic (Appendix 3, page 33). In the case of study area 17 the low quality is most likely caused by a lack of overlap in the images. The actual percentage of image overlap could not be determined but the number of images (25 images) for area 17 was significantly lower than that of the others (between 80 to 150).

When the results of the models are compared with the manual digitized tree and the field data there is a possibility for human error that can be of influence on the results. This is due to the fact that the manual digitized tree data were created by hand as well as the measured field data by human measurements.

Also, the fact that the average measured field data could only be compared with the models averages can cause a bias in the results. Comparing averages of two different data sets can present results that seem similar but in fact have very different source values. This can be the case with the designed models that sometimes return very high or low parameter values. The success rate calculated through the standard deviation during the quality evaluation attempts to eliminate this factor. Nonetheless, the chance of biasing in this case remains when comparing averages.

Studies for tree crown differentiation or finding heights have been done in different setups and following various methods. For this reason it is difficult to compare best performing models to similar studies. In Kallimani's study it has been found that for individual tree crown detection using the local maxima tool similar to model 2 an accuracy of 69% (Kallimani, 2016). The study Kallimani did is very similar to this thesis study, applied to the forest of Kalimantan but in this case using LIDAR scanning technology. Kallimani's accuracy is lower than that of model 2, which showed 84% accuracy. In this case the success rate that has performed on model 2 values needs to be taken into account. Considering that 82% was successful and 18% was rejected of model 2 height values before the accuracy test took place. Therefore, model 2 scored most likely lower than Kallimani's research. The watershed segmentation as used in model 5 performed poorly on the Sarawak data set with only around 60% success rate and 64% accuracy. According to the literature of *"A benchmark of LIDAR-based single tree detection methods using heterogeneous forest data from the Alpine Space"* of Eysn et al. this method performed 76% accurate (Eysn et al., 2015). The reason for the different results could origin from the input data set. The benchmark test applies the method to alpine forest that is very differently structured compared to the Sarawak data set. Also, Eysn describes using a set of filters before using the watershed segmentation tool. These filters were not available within Quantum GIS and could not be included in model 5.

Image Classification claims the highest accuracy of tree height, tree shape and canopy cover detection up to 90% (Yang, Wu, Praun, & Ma, 2009). This is based on a study in an urbanized setting using LIDAR data sets. In different circumstances and with a different data set, image classification has most likely the highest potential for the dense forest as it is found in Sarawak. If trees can be successfully differentiated and depending on the image quality species differentiation and recognition is an option. Although the available data set for this study is not suited for species differentiation due to a lack of spectral bands, the possibility remains if further recordings are taken with more advanced UAV equipment. Different studies offer guidelines and possibilities to apply species recognition with the right data set (Colgan et al., 2012).

Above ground carbon stock estimations can be calculated through forest parameters that can be obtained by the designed models. Most commonly this is done through the parameters: tree height, perimeter, crown area and DBH (Diameter at Breast Height)(R.A.Singh, 2003). Since the DBH cannot be extracted from the Sarawak drone image data set, allometric relation formulas have to be applied in order to estimate the carbon stocks. The study "*Allometric equations for estimating the above-ground biomass in tropical lowland dipterocarp forests"* done by Basuki et al, presents specific calculation equations to calculate DBH and biomass specific for lowland dipterocarp forests (Basuki, van Laake, Skidmore, & Hussin, 2009). These methods are also known as the allometric relation methods (Lockhart, Weih, & Smith, 2005).The obtained DBH through these allometric relations can also be used to estimate timber stocks for sustainable timber extraction. Forest density is also one of the important factors when estimating carbon stocks over a large area. Forest density is related to canopy cover for which model 6 was designed. Besides carbon stock estimation canopy cover can also help to track structural forest changes as well as offering the potential to track deforestation and forest succession.

5. Conclusion

This study demonstrates that forest parameters can be extracted from UAV images of the canopy of the forest in Sarawak through open-source software packages. The achievable forest parameters are: tree height, tree crown perimeter, tree crown area, and canopy cover. Six different models have been designed, each to at least extract one forest parameter.

The most successful models per parameter are presented in Table 10, which gives an overview of their success and accuracy rates.

To answer the research questions:

Research Question 1*:* *How can the tree crown heights, perimeter, area and canopy cover can be derived from UAV image data using open source software packages?*

Tree heights, perimeter, area and canopy cover can be achieved derived from UAV image data through models designed in open source software package Quantum GIS.

Research Question 2: *How accurate are the derived forest parameters compared to manual reference data?*

The derived parameters perform respectively accurate when comparing to manual reference data: as stated in Table 10.

Table 10, Results of Best Performing Methods with their Accuracy Results

Most Successful Models per Parameter	Model	Success Rate	Accuracy
Tree Height Detection	Model 2	82%	84%
Tree Perimeter Detection	Model 4	78%	76%
Tree Area Detection	Model 4	75%	82%
Canopy Cover Detection	Model 6	N/A	97%

5.1. Recommendations

Further studies should investigate in improving the designed models towards higher success rates and more accurate results. As well as make them adapt to other forest types that are different than the Sarawak data set forest type. The potential of licensed software packages has not been explored in this study and could offer some new insights. When performing further research on this subject in a similar setting it is recommended to capture accurate GPS positions of the reference trees. This enables one on one comparison for more accurate testing results. For further UAV supported forest inventories it is advisable to consider investing in LIDAR sensors for more detailed point clouds and 3D mapping of the forest canopy. Additional sensors open the possibilities for more advanced detection tools with the option to obtain additional and more accurate forest parameters.

6. References

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7. Appendices

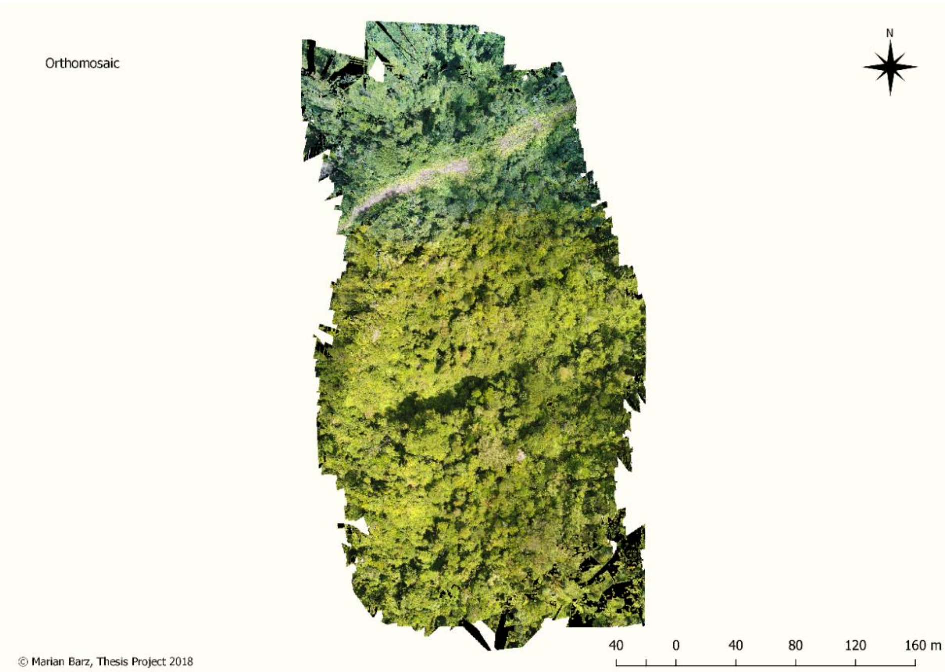
Appendix 1, Study Area Location GPS Coordinates

Study area ID	E	N
1	113.57711	2.35806
16	113.10325	1.56484
17	114.12054	1.77798
5	114.27388	1.78364
14	112.76656	1.59494

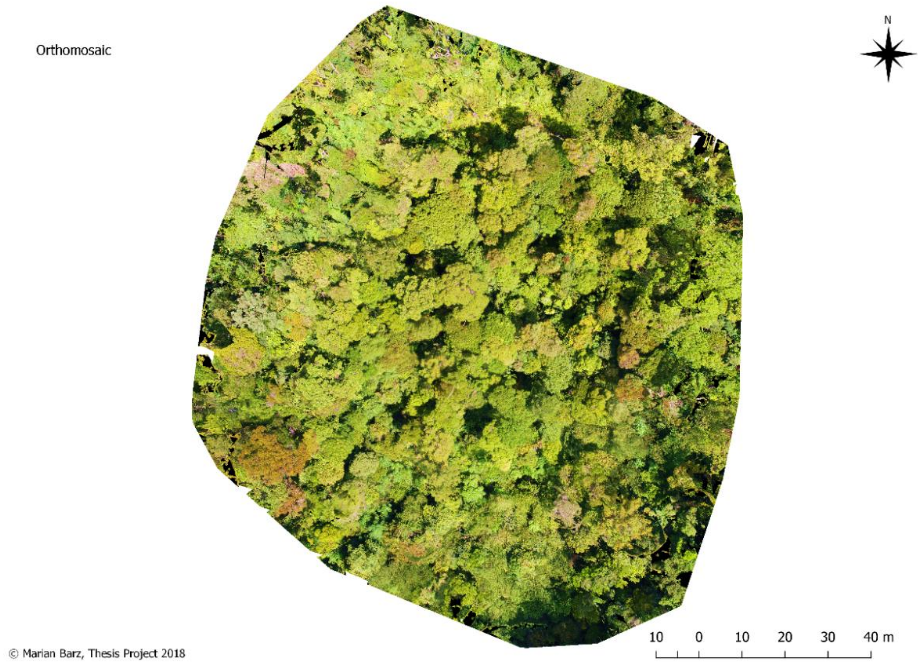
Appendix 2, Drone Specifications

The drone type that was used was the Phantom 4 Pro. It has a maximum flight time of approximately 30 minutes ("Phantom 4 Pro - Professional aerial filmmaking made easy," n.d.). For flight software the DJI GO 4 package was used to determine the flight path. It was equipped with a RGB (Red, Green, Blue color spectrum) camera with a resolution of *5472x3078 (aspect ratio 16:9) or* 4864 × 3648 (aspect ratio 4:3) with 20Mb in JPEG or DNG (RAW) format and no additional sensors. The drone was controlled manually and the pictures were taken between 50 and 200 meters height. This resulted in picture sets of 5 areas that have been made available for this study

Appendix 3, Orthomosaic of All Available Study Area Locations

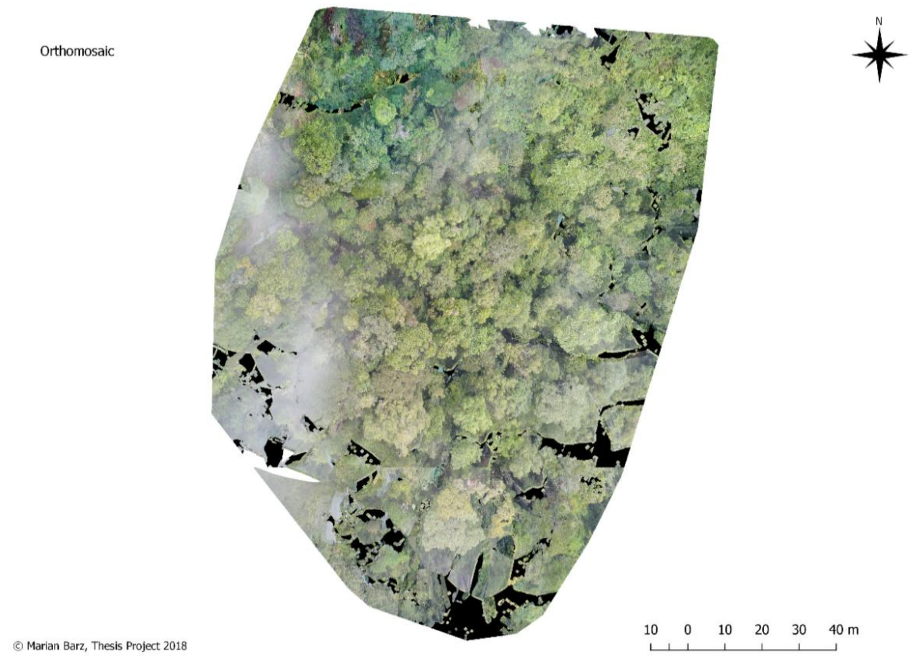


Appendix Figure 1 Orthomosaic of Study Area 1

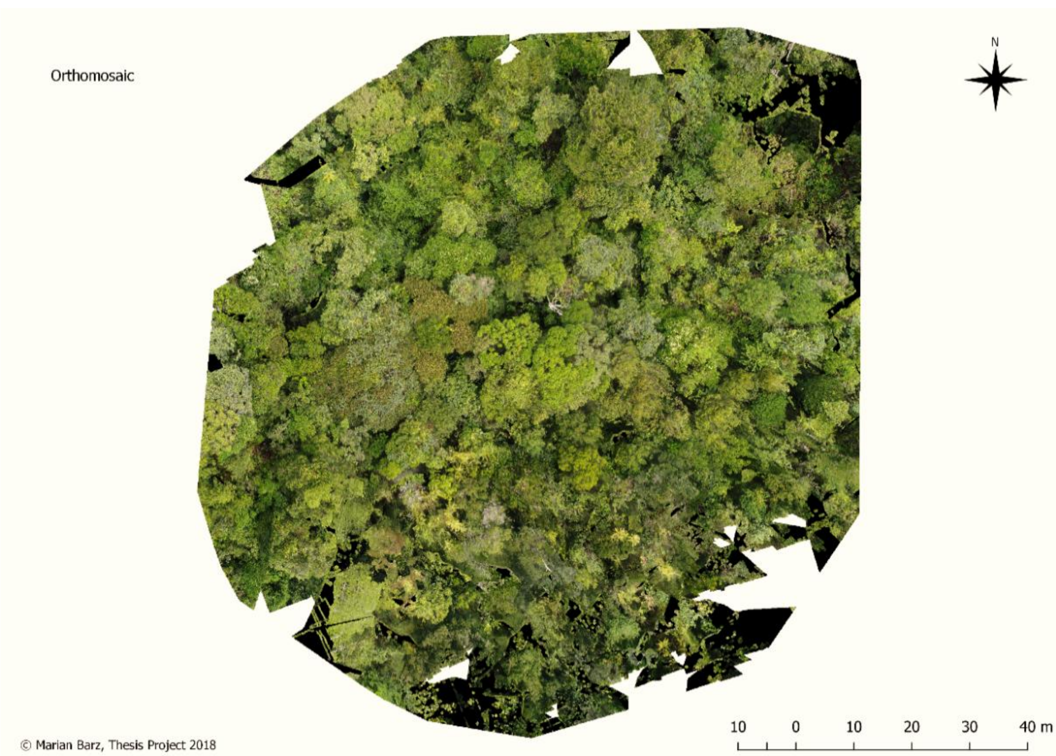


Appendix Figure 2, Orthomosaic of Study Area 5

Appendix Figure 3, Orthomosaic of Study Area 14



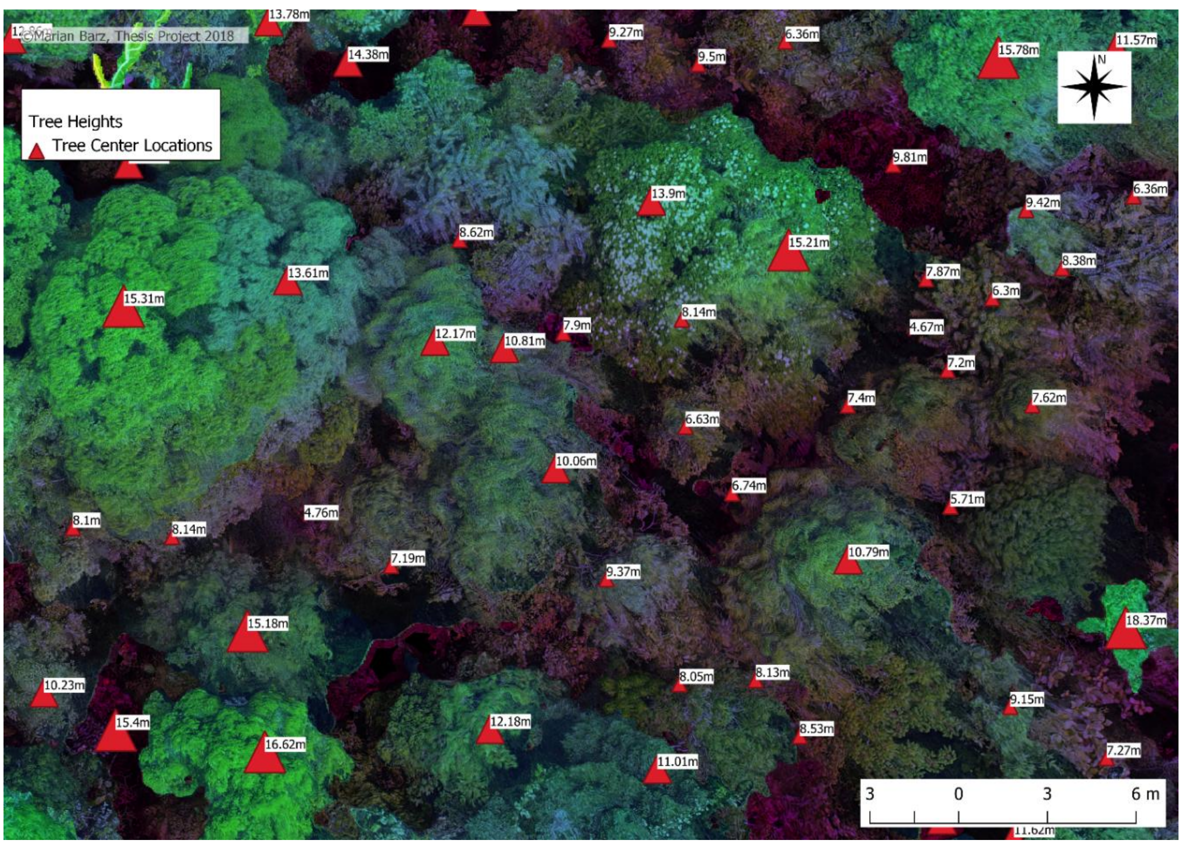
Appendix Figure 4, Orthomosaic of Study Area 16



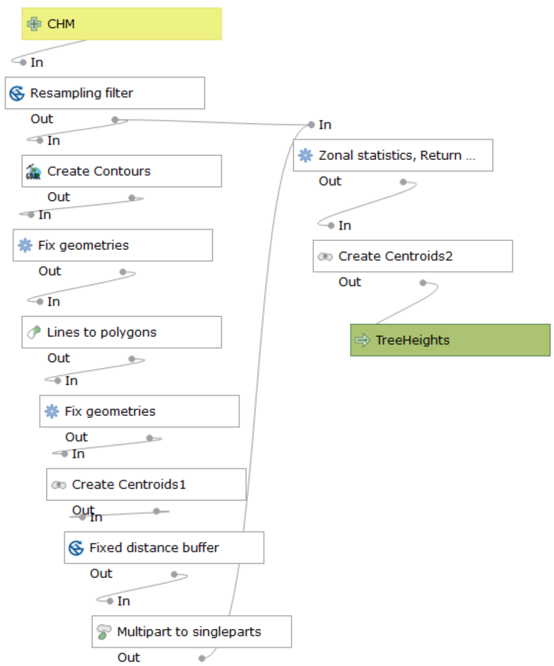
Appendix Figure 5, Orthomosaic of Study Area 17

Appendix 4, Description Model 1, Contour Approach (Model 1)

Model 1 creates height contour lines from the canopy height model with the contour tool and converts them into polygons using the lines to polygon tool. A contour line interval of 0.2 meters was found to be the most efficient for this model. Some of the created polygons had invalid geometry, meaning that the shape of the polygon is not like that of a tree crown, these polygons are filtered out to prevent calculation errors with the fix geometry tool. By using the extract by attribute tool to filter out polygons with either a too large or too small geometry and eliminate them from the data set, leaving only realistic tree crowns shape sizes. A realistic tree crown area was manually determined to be approximately 180 m2 with a perimeter 30 m; this is what the elimination criteria was based upon. With the create centroid tool center points of each polygons are then calculated, this results in a cluster of centroids at the location where the tree crown should be located. The centroids are then buffered, which creates an area around each centroid with a radius of 1.5 meters. Where there is a cluster of centroids, the buffer zones overlap each other. The overlapping areas are then merged together, using the multipart to single parts tool, which results in one polygon for each cluster of points. The zonal statistic tool then calculates the highest elevation values within each polygon and that value is used as the treetop as show in Appendix Figure 6. This model was designed in Quantum GIS 2.18.16 with the SAGA 2.3.2 and GRASS GIS 7 tool set. The workflow is presented in Appendix Figure 7.

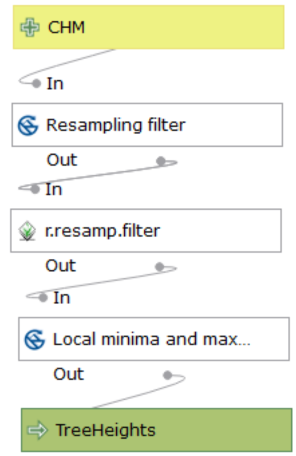


Appendix Figure 6, Results of the Contour Approach, Detecting Tree Heights With Model 1

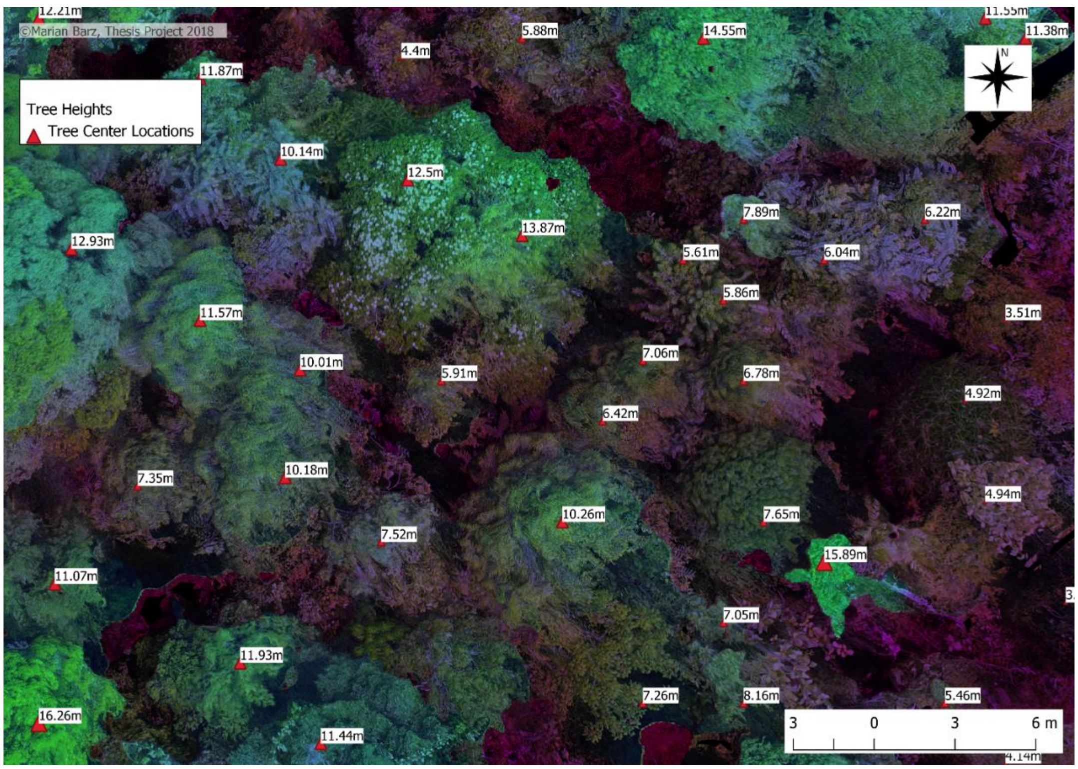


Appendix Figure 7, Workflow Model 1

In Model 2 uses filtered canopy height model is run through a resample filter from GRASS GIS 7 to increase the pixel kernels and return the average value from its neighbors. The neighborhood radius is kept low to reduce averaging of a too large area, a value of 0.1 was found the most suited to get the best results. The cell size is very important when it comes to differentiating between different trees as it determines the image pixel grid size. A grid size of 0.8 meter was found most successful to detect small and large tree crowns. Next the Local maxima tool is used that will look within a the neighborhood of the each pixel in the grid for maximum values and returns them (Appendix Figure 9). This model was designed in Quantum GIS 3.2.1 with the SAGA 2.3.2 and GRASS GIS 7 tool set. The workflow is presented in Appendix Figure 8.



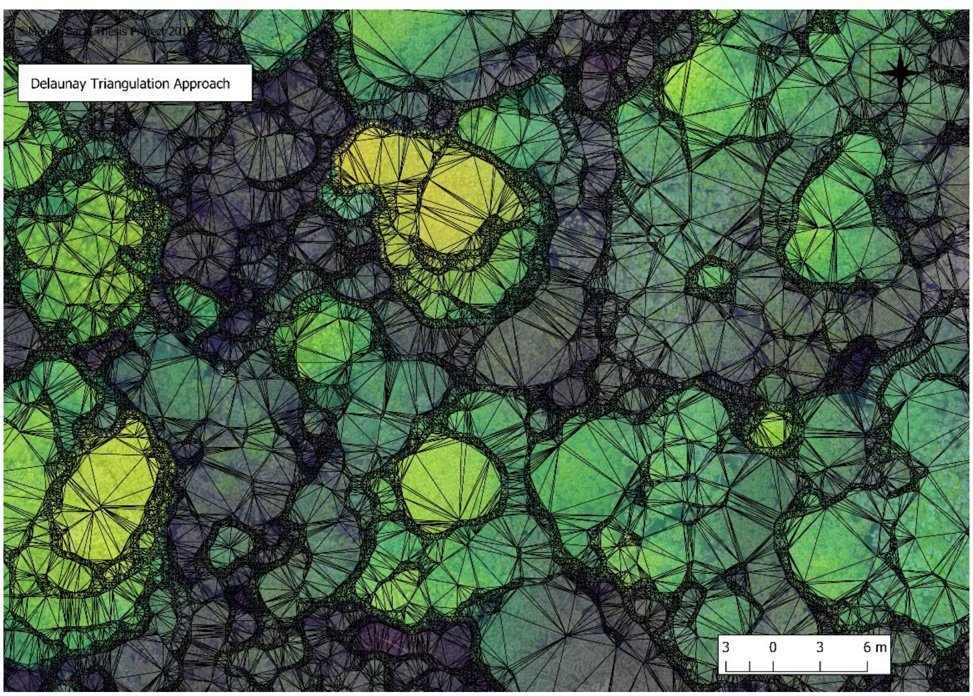
Appendix Figure 8, Workflow Model 2



Appendix Figure 9, Result of Model 2 the Filter Approach, Presenting Tree Center Locations With their Calculated Heights.

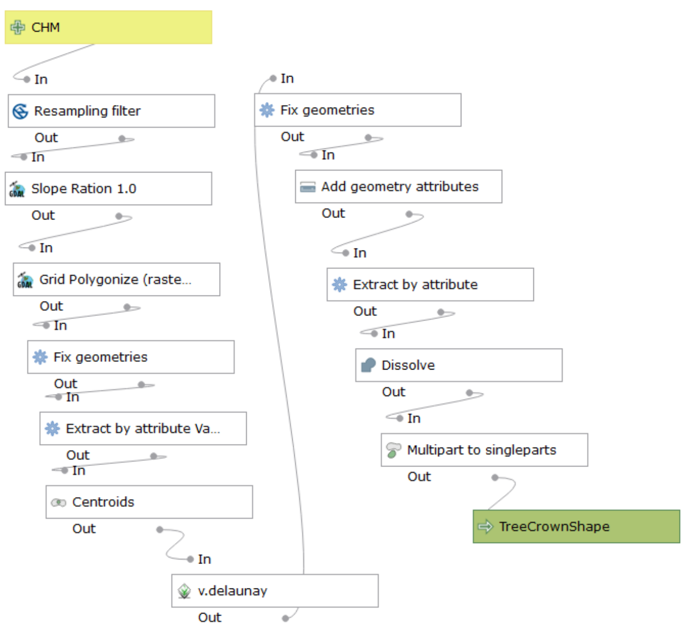
Appendix 6, Description Model 3, Delaunay Triangulation Approach (Model 3)

Model 3 creates an slope aspect map from the canopy height model by calculating the standard deviation of each pixel in the canopy height model and scales them from 0 to 90 to convert the slope values to degrees. The slope aspect is used to define the tree crown edges because naturally the slope aspect has a higher value towards the edges of a tree crown. The aspect slope map is then vectorized which converts the map in to small polygons. Each polygon has the values from the aspect slope. Polygons with a aspect slope value of 75 to 90 degrees are then filtered out. This is the parameter which defines the tree crown edge. The polygons are converted to points by the create centroid tool. The delaunay triangulation algorithm tool is than connecting each point with at least two of its closes neighboring points resulting in the area between all points being filled with triangular shaped polygons (Lee & Schachter, 1980) (Appendix Figure 10). Due to the lack of slope in the center of a tree crown the triangles have a bigger area than close to the edge of the tree crown. Small polygons are than filtered by the extract by attribute tool to remove the edges of the tree crowns where the aspect slope is high. The larger neighboring polygons are joined together by the dissolve tool and the geometries are calculated for each tree through the add geometry attributes tool (Appendix Figure 11). This model was designed in Quantum GIS 3.2.1 with the SAGA 2.3.2 and GRASS GIS 7 tool set. The workflow is presented in Appendix Figure 12.



Appendix Figure 10, Results of the Delaunay Triangulation Tool Derived from Aspect Slope Centroids, Demonstrating Model 3

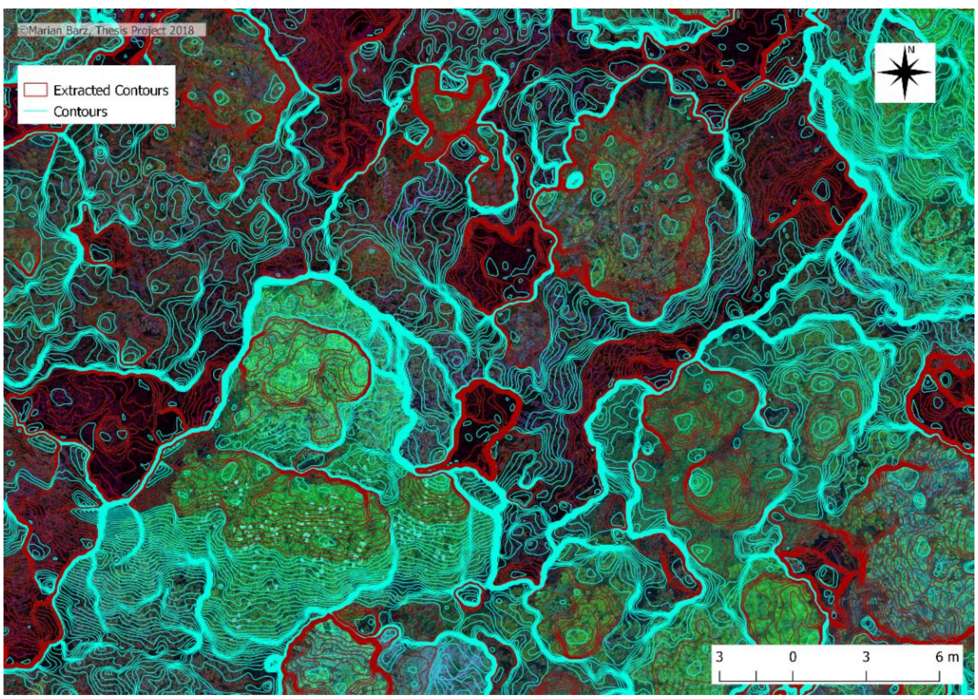
Appendix Figure 11, Result of the Delaunay Triangulation Tool Derived from Aspect Slope Centroids Filtered and Polygonised, Demonstrating Model 3.



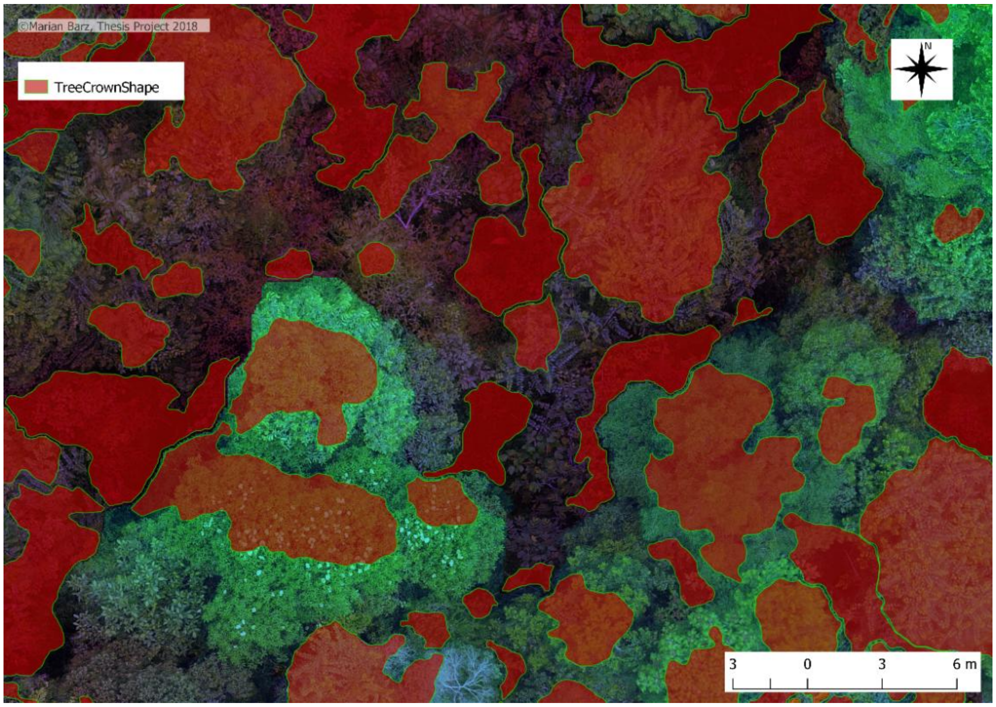
Appendix Figure 12, Workflow Model 3

Appendix 7, Description Model 4, the Contour Approach 2 (Model 4)

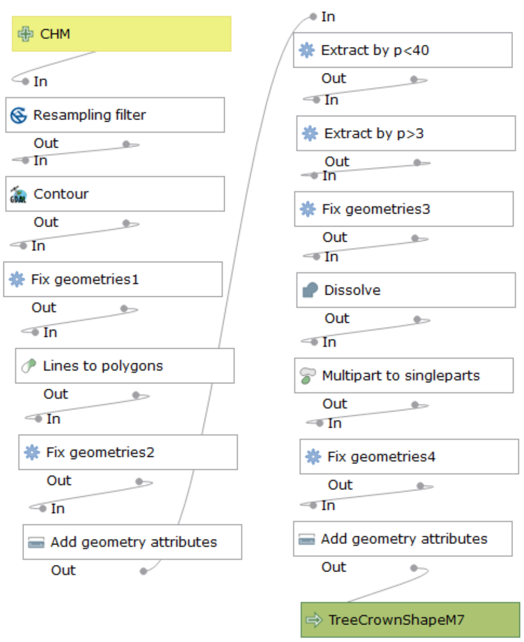
Model 4 also uses the contour tool, similar to model 1 but this time with a even lower interval of 0.2 meters (Appendix Figure 13). These contours are than converted into polygons with the lines to polygon tool. The add geometry tool calculates the perimeter and area values of each of the created polygons. Perimeters between 3 and 40 meters are than extracted from the data set and are designated as tree crowns. The perimeter values that determine the tree crowns for extraction were determined by the average tree perimeter values. Overlapping polygons are then joined together with the dissolve tool to have one polygon represent each tree crown. (Appendix Figure 14). This model was designed in Quantum GIS 2.18.16 with the SAGA 2.3.2 and GRASS GIS 7 tool set. The workflow is presented in Appendix Figure 15.



Appendix Figure 13, Result of the Contour Approach 2 Before Filtering Demonstrating Model 4



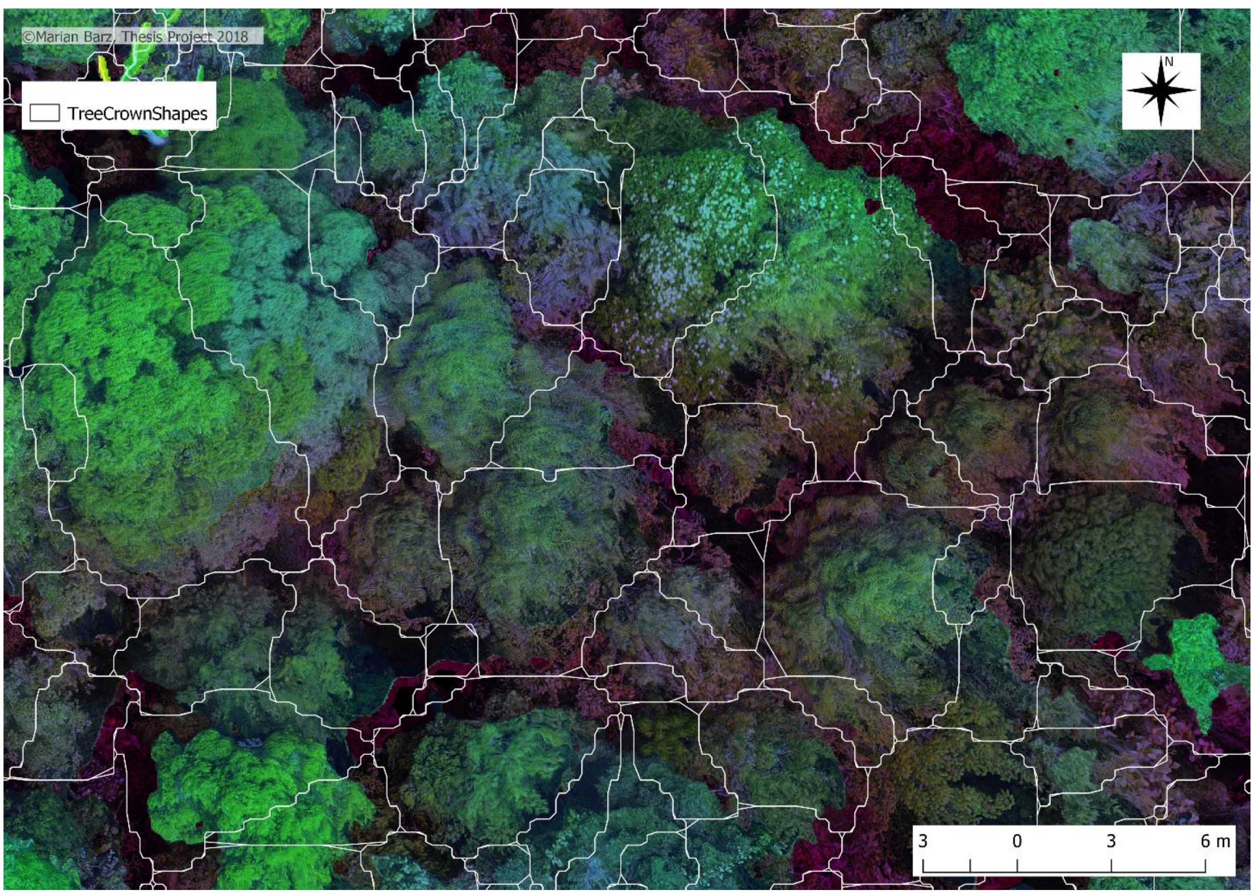
Appendix Figure 14, Result of the Contour Approach 2 Presenting Tree Crown Shapes with their Calculated Areas, Model 4



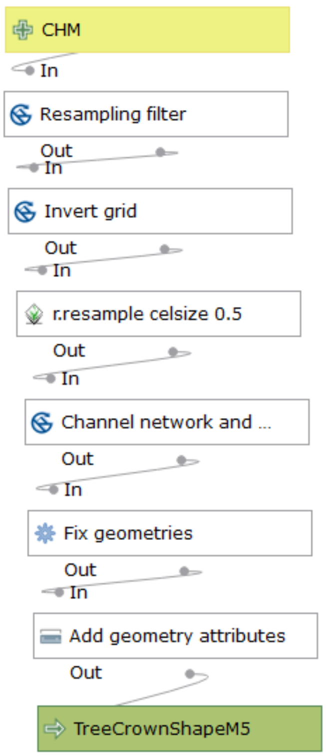
Appendix Figure 15, Workflow of Model 4

Appendix 8, Description Model 5, the Watershed Segmentation Approach (Model 5)

Model 5 is based on the watershed segmentation tools. On the canopy height model the invert grid tool is applied that converts high pixel values into low values and low values into high values. The pixel size is than changed with the resample tool into a more workable format for the next tool. A pixel grid size of 0.5m was found to be the most suited for tree crown shape extraction. In the next step the channel network and watershed segmentation tool is applied. The watershed tool fills virtually the inverted canopy height model with water and returns the areas where the water would stagnate as an output. Since the tree crowns are mostly cylindrical shaped and inverted, the cylinders fill up until it joins with another tree crown cylinder. The result is than segmented in to polygons so that each polygon represents the outline of a tree crown (Appendix Figure 16). Through the add geometry tool the perimeter and area can be calculated and assigned to each individual tree crown. This model was designed in Quantum GIS 3.2.1 with the SAGA 2.3.2 and GRASS GIS 7 tool set. The workflow is presented in Appendix Figure 17.

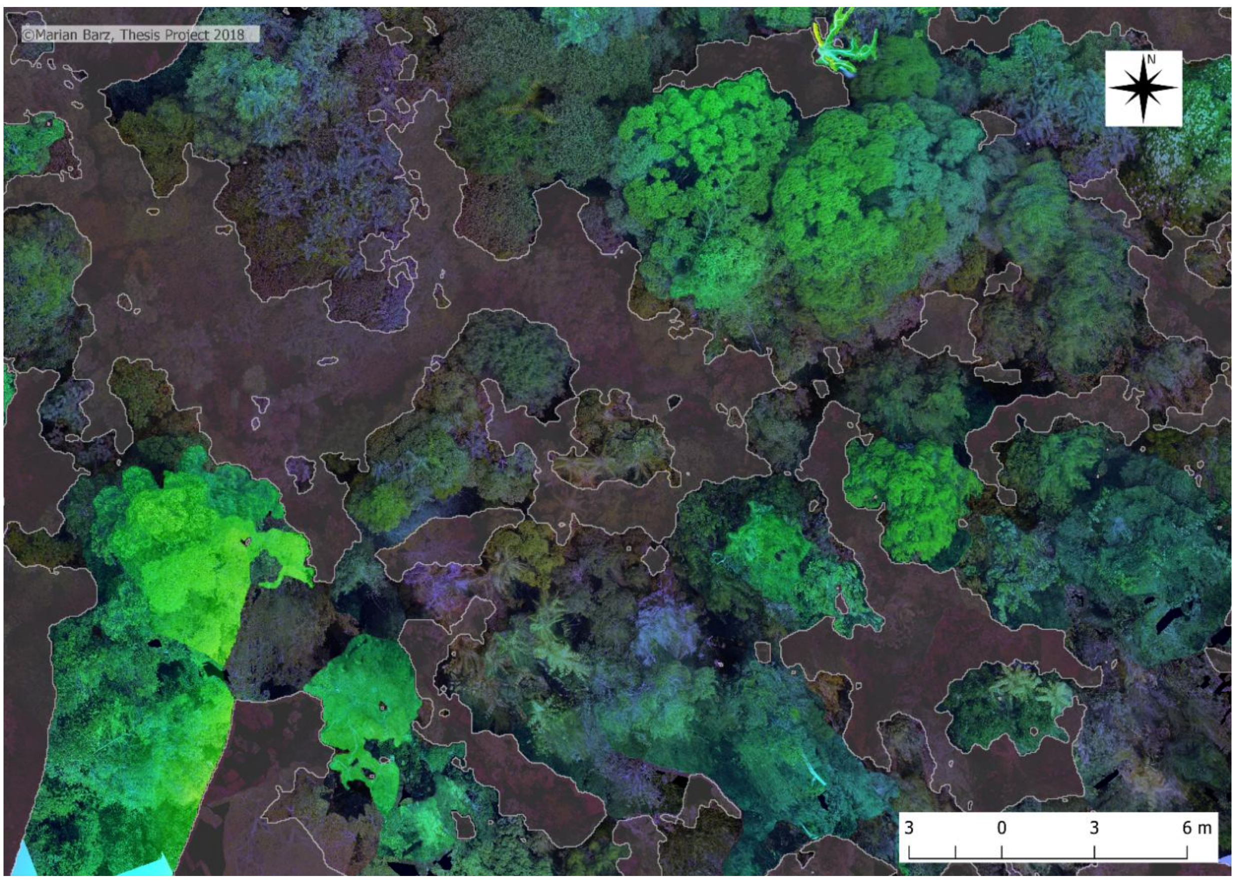


Appendix Figure 16, Result of the Watershed Segmentation Approach Model 5, Presenting Tree shape Segments.

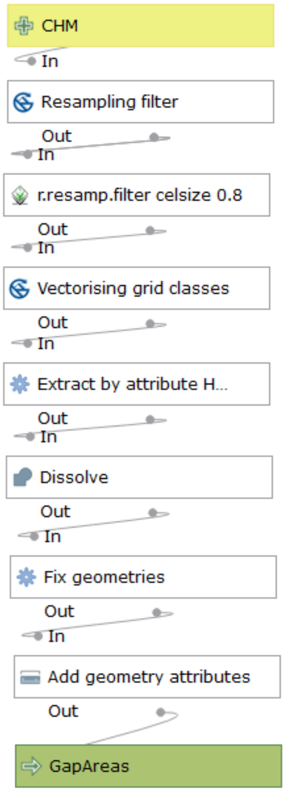


Appendix Figure 17, Workflow of Model 5

Forest gaps and low vegetation are defined by areas with a low canopy height model value. Model 6 that is used for this is very similar to Model 5 except for the inversion of the canopy height model and the segmentation. In Model 6 the canopy height model is resampled to a more suited kernel size, 0.8 was found to be most accurate and is then vectorized which results in a grid with 0.8 x 0.8 cells with the height data embedded. Since there is only low vegetation to be expected in a forest gap the maximum vegetation height is set for 3m and below, this parameter defines that there is only low vegetation in this area and thus classified as a forest gap (Appendix Figure 18). Rough study area locations that were made available by the Sarawak Forestry Corporation were reconstructed as good as possible and the results of Model 6, gap area was extracted for each study area and converted to a percentage of canopy cover. The results were then compared with the findings of the Sarawak Forestry Corporation and are presented in chapter 3.3. This model was designed in Quantum GIS 3.2.1 with the SAGA 2.3.2 and GRASS GIS 7 tool set. The workflow is presented in Appendix Figure 19.



Appendix Figure 18, Results of Model 6, Canopy cover detection Approach, Presenting Forest Gap Areas.



Appendix Figure 19, Workflow Model 6

Appendix 10, Models Detection Success Rate

Appendix Table 1, Model 1 Height Detection Success Rate

Heights Model 1 Results	
Average Stdev. (σ) Model	2.78
Average Stdev. (σ) MDT	1.89
Total records	219
Successful Detections	149
Success Rate	68%

Appendix Table 2, Model 2 Height Detection Success Rate

Heights Model 2 Results	
Average Stdev. (σ) Model	1.14
Average Stdev. (σ) MDT	0.93
Total records	215
Successful Detections	176
Success Rate	82%

Appendix Table 3, Model 3 Perimeter Detection Success Rate

Perimeter Model 3 Results	
Average Stdev. (σ) Model	15.06
Average Stdev. (σ) MDT	11.60
Total records	221
Successful Detections	171
Success Rate	77%

Appendix Table 4, Model 4 Perimeter Detection Success Rate

Perimeter Model 4 Results	
Average Stdev. (σ) Model	13.00
Average Stdev. (σ) MDT	10.14
Total records	217
Successful Detections	169
Success Rate	78%

Appendix Table 5, Model 5 Perimeter Detection Success Rate

Perimeter Model 5 Results	
Average Stdev. (σ) Model	10.41
Average Stdev. (σ) MDT	6.04
Total records	219
Successful Detections	127
Success Rate	58%

Appendix Table 6, Model 3 Area Detection Success Rate

Area Model 3 Results	
Average Stdev. (σ) Model	23.29
Average Stdev. (σ) MDT	17.70
Total records	221
Successful Detections	167
Success Rate	76%

Appendix Table 7, Model 4 Area Detection Success Rate

Area Model 4 Results	
Average Stdev. (σ) Model	13.32
Average Stdev. (σ) MDT	9.99
Total records	217
Successful Detections	161
Success Rate	75%

Appendix Table 8, Model 5 Area Detection Success Rate

Area Model 5 Results	
Average Stdev. (σ) Model	21.54
Average Stdev. (σ) MDT	13.57
Total records	219
Successful Detections	139
Success Rate	63%

MDT – Manual Digitized Tree

Appendix 11, Model 1 and Manual Height Data from All Study Areas

ID	Study area	Manual Heights	M1 Heights	Accuracy	Stdev.
13	1	16.92	14.47	0.86	1.23
38	1	32.09	28.56	0.89	1.76
36	1	28.43	25.61	0.90	1.41
21	1	53.73	49.03	0.91	2.35
19	1	44.50	40.71	0.91	1.89
1	1	39.53	36.28	0.92	1.63
7	1	17.80	16.44	0.92	0.68
5	1	49.71	46.79	0.94	1.46
35	1	17.76	18.67	0.95	0.46
32	1	27.71	26.52	0.96	0.59
20	1	48.22	46.28	0.96	0.97
22	1	31.91	33.14	0.96	0.61
33	1	5.35	-	-	2.67
39	1	39.43	38.30	0.97	0.56
15	1	16.17	15.72	0.97	0.22
4	1	49.86	48.81	0.98	0.52
25	1	32.70	32.11	0.98	0.30
3	1	39.10	38.78	0.99	0.16
31	1	22.93	22.78	0.99	0.07
10	1	28.73	28.60	1.00	0.06
26	1	45.19	45.03	1.00	0.08
12	1	29.62	29.60	1.00	0.01
34	1	11.97	11.97	1.00	0.00
30	1	16.23	16.23	1.00	0.00
17	1	16.85	16.85	1.00	0.00
42	1	21.39	21.39	1.00	0.00
28	1	21.76	21.76	1.00	0.00
37	1	23.41	23.41	1.00	0.00
11	1	23.91	23.91	1.00	0.00
8	1	25.42	25.42	1.00	0.00
27	1	26.74	26.74	1.00	0.00
14	1	27.86	27.86	1.00	0.00
29	1	31.67	31.67	1.00	0.00
20	5	15.95	10.76	0.67	2.59
1	5	26.66	21.86	0.82	2.40
22	5	20.37	16.90	0.83	1.73
43	5	12.66	14.05	0.90	0.70
26	5	18.55	16.83	0.91	0.86
5	5	24.58	22.38	0.91	1.10
29	5	20.83	18.99	0.91	0.92
12	5	13.73	12.72	0.93	0.51
10	5	25.23	23.59	0.94	0.82
30	5	20.71	19.38	0.94	0.67
13	5	8.30	7.88	0.95	0.21
28	5	19.61	18.71	0.95	0.45
18	5	23.10	22.08	0.96	0.51
42	5	20.48	19.78	0.97	0.35
15	5	16.56	16.03	0.97	0.27

Appendix 12, Model 2 and Manual Height Data from All Study Areas

ID	Study area	Manual Heights	M2 Heights	Accuracy	Stdev.
1	1	39.53	39.30	0.99	0.12
2	1	24.39		-	0.00
3	1	39.10	38.04	0.97	0.53
4	1	49.86	48.43	0.97	0.71
5	1	49.71	48.85	0.98	0.43
6	1	26.95	26.11	0.97	0.42
7	1	17.80	17.25	0.97	0.27
8	1	25.42	25.09	0.99	0.17
9	1	16.66	16.35	0.98	0.16
10	1	28.73	28.20	0.98	0.27
11	1	23.91	23.44	0.98	0.24
12	1	29.62	29.25	0.99	0.18
14	1	27.86	27.20	0.98	0.33
15	1	16.17	15.61	0.97	0.28
16	1	8.93	7.81	0.87	0.56
17	1	16.85	16.64	0.99	0.11
19	1	44.50	43.53	0.98	0.48
23	1	26.07	25.73	0.99	0.17
24	1	23.02	-	-	0.00
25	1	32.70	30.91	0.95	0.90
26	1	45.19	44.70	0.99	0.25
27	1	26.74	26.26	0.98	0.24
28	1	21.76	21.23	0.98	0.26
29	1	31.67	31.13	0.98	0.27
30	1	16.23	15.84	0.98	0.19
31	1	22.93	22.47	0.98	0.23
32	1	27.71	27.11	0.98	0.30
33	1	5.35	4.76	0.89	0.29
34	1	11.97	11.29	0.94	0.34
35	1	17.76	17.48	0.98	0.14
36	1	28.43	27.72	0.98	0.35
37	1	23.41	22.54	0.96	0.43
38	1	32.09	31.25	0.97	0.42
39	1	39.43	38.24	0.97	0.59
40	1	25.66	-	-	0.00
41	1	24.74	-	-	0.00
42	1	21.39	20.64	0.96	0.38
2	5	14.89	14.19	0.95	0.35
5	5	24.58	23.07	0.94	0.76
6	5	8.90	7.34	0.82	0.78
7	5	18.40	18.08	0.98	0.16
8	5	17.26	16.70	0.97	0.28
9	5	22.44	21.42	0.95	0.51
10	5	25.23	24.34	0.96	0.44
11	5	17.50	16.67	0.95	0.42
12	5	13.73	12.31	0.90	0.71
13	5	8.30	8.01	0.97	0.14

9	5	22.44	21.92	0.98	0.26
11	5	17.50	17.12	0.98	0.19
8	5	17.26	17.23	1.00	0.02
2	5	14.89	14.89	1.00	0.00
19	5	15.31	15.31	1.00	0.00
34	5	16.23	16.23	1.00	0.00
7	5	18.40	18.40	1.00	0.00
33	5	19.88	19.88	1.00	0.00
21	5	21.34	21.34	1.00	0.00
38	5	28.97	28.97	1.00	0.00
46	14	10.83	6.46	0.60	2.18
6	14	9.42	13.80	0.68	2.19
42	14	14.34	10.57	0.74	1.89
7	14	10.97	8.10	0.74	1.43
62	14	6.52	8.55	0.76	1.01
24	14	29.65	24.33	0.82	2.66
1	14	11.39	9.46	0.83	0.97
22	14	24.27	20.45	0.84	1.91
21	14	25.69	21.86	0.85	1.91
19	14	19.29	16.53	0.86	1.38
27	14	26.56	23.17	0.87	1.69
12	14	12.18	10.73	0.88	0.72
28	14	28.82	26.12	0.91	1.35
13	14	17.01	15.43	0.91	0.79
47	14	15.36	13.94	0.91	0.71
48	14	21.79	19.88	0.91	0.95
26	14	20.29	18.72	0.92	0.78
54	14	14.84	13.73	0.93	0.56
58	14	18.25	17.07	0.94	0.59
40	14	17.43	16.67	0.96	0.38
49	14	15.43	14.80	0.96	0.32
39	14	20.04	19.44	0.97	0.30
23	14	16.20	15.75	0.97	0.23
2	14	14.44	14.07	0.97	0.18
45	14	15.90	15.54	0.98	0.18
52	14	21.31	21.01	0.99	0.15
37	14	16.46	16.23	0.99	0.12
25	14	22.78	22.59	0.99	0.10
43	14	14.92	14.82	0.99	0.05
3	14	15.68	15.58	0.99	0.05
29	14	18.62	18.54	1.00	0.04
50	14	17.96	17.90	1.00	0.03
41	14	9.14	9.14	1.00	0.00
5	14	9.66	9.66	1.00	0.00
60	14	10.30	10.30	1.00	0.00
4	14	10.90	10.90	1.00	0.00
10	14	12.38	12.38	1.00	0.00
44	14	12.66	12.66	1.00	0.00
38	14	13.29	13.29	1.00	0.00
31	14	15.16	15.16	1.00	0.00
34	14	15.52	15.52	1.00	0.00

15	5	16.56	14.99	0.91	0.79
18	5	23.10	22.61	0.98	0.25
19	5	15.31	14.92	0.97	0.20
21	5	21.34	20.89	0.98	0.23
22	5	20.37	18.59	0.91	0.89
26	5	18.55	17.77	0.96	0.39
27	5	11.82	11.26	0.95	0.28
28	5	19.61	17.91	0.91	0.85
29	5	20.83	19.32	0.93	0.75
30	5	20.71	19.88	0.96	0.41
33	5	19.88	19.06	0.96	0.41
34	5	16.23	14.80	0.91	0.71
38	5	28.97	27.74	0.96	0.61
39	5	7.05	6.40	0.91	0.32
40	5	20.03	19.38	0.97	0.33
42	5	20.48	18.68	0.91	0.90
2	14	14.44	14.00	0.97	0.22
3	14	15.68	15.30	0.98	0.19
4	14	10.90	8.71	0.80	1.09
5	14	9.66	9.13	0.95	0.26
6	14	9.42	8.69	0.92	0.37
9	14	21.76	20.82	0.96	0.47
10	14	12.38	11.65	0.94	0.37
11	14	18.64	17.77	0.95	0.44
12	14	12.18	11.84	0.97	0.17
13	14	17.01	16.55	0.97	0.23
14	14	11.76	11.02	0.94	0.37
15	14	11.43	11.02	0.96	0.21
17	14	10.54	8.45	0.80	1.04
19	14	19.29	17.52	0.91	0.88
20	14	19.71	18.24	0.93	0.74
21	14	25.69	24.20	0.94	0.74
22	14	24.27	22.36	0.92	0.95
23	14	16.20	14.90	0.92	0.65
24	14	29.65	27.60	0.93	1.02
25	14	22.78	22.06	0.97	0.36
26	14	20.29	18.25	0.90	1.02
28	14	28.82	27.18	0.94	0.82
29	14	18.62	18.35	0.99	0.13
30	14	15.75	15.24	0.97	0.26
31	14	15.16	14.96	0.99	0.10
33	14	13.10	12.58	0.96	0.26
34	14	15.52	14.68	0.95	0.42
35	14	17.20	16.67	0.97	0.27
37	14	16.46	15.91	0.97	0.27
38	14	13.29	12.86	0.97	0.21
39	14	20.04	19.71	0.98	0.16
40	14	17.43	16.83	0.97	0.30
41	14	9.14	8.48	0.93	0.33
42	14	14.34	13.78	0.96	0.28
43	14	14.92	14.47	0.97	0.22

30	14	15.75	15.75	1.00	0.00
35	14	17.20	17.20	1.00	0.00
11	14	18.64	18.64	1.00	0.00
20	14	19.71	19.71	1.00	0.00
55	14	21.44	21.44	1.00	0.00
9	14	21.76	21.76	1.00	0.00
63	14	4.79	-	-	2.40
4	16	20.30	16.72	0.82	1.79
22	16	14.18	11.94	0.84	1.12
20	16	15.21	13.23	0.87	0.99
21	16	8.12	7.19	0.89	0.47
9	16	16.66	14.92	0.90	0.87
18	16	10.82	9.89	0.91	0.47
16	16	12.17	11.36	0.93	0.40
2	16	15.28	14.38	0.94	0.45
11	16	14.75	14.02	0.95	0.36
13	16	15.68	14.92	0.95	0.38
17	16	16.62	16.58	1.00	0.02
5	16	9.84	9.84	1.00	0.00
1	16	9.86	9.86	1.00	0.00
14	16	12.73	12.73	1.00	0.00
15	16	15.31	15.31	1.00	0.00
12	16	16.17	16.17	1.00	0.00
16	17	9.94	5.38	0.54	2.28
43	17	15.80	11.70	0.74	2.05
24	17	21.07	15.81	0.75	2.63
39	17	20.57	15.68	0.76	2.44
31	17	17.05	13.73	0.80	1.66
32	17	13.95	12.17	0.87	0.89
27	17	16.85	14.76	0.88	1.04
38	17	19.77	17.68	0.89	1.04
34	17	25.54	23.57	0.92	0.98
23	17	20.79	19.53	0.94	0.63
1	17	20.19	19.39	0.96	0.40
36	17	13.42	12.89	0.96	0.26
46	17	18.99	18.27	0.96	0.36
15	17	18.16	17.69	0.97	0.24
8	17	15.54	15.27	0.98	0.13
41	17	16.86	16.60	0.98	0.13
25	17	8.75	8.70	0.99	0.02
28	17	9.44	9.44	1.00	0.00
17	17	12.79	12.79	1.00	0.00
33	17	15.74	15.74	1.00	0.00
42	17	16.02	16.02	1.00	0.00
7	17	18.04	18.04	1.00	0.00
11	17	18.15	18.15	1.00	0.00
10	17	18.72	18.72	1.00	0.00
35	17	19.43	19.43	1.00	0.00
5	17	19.92	19.92	1.00	0.00
45	17	21.96	21.96	1.00	0.00

44	14	12.66	12.30	0.97	0.18
45	14	15.90	14.99	0.94	0.45
46	14	10.83	10.59	0.98	0.12
47	14	15.36	15.11	0.98	0.12
49	14	15.43	15.05	0.98	0.19
50	14	17.96	17.28	0.96	0.34
52	14	21.31	20.85	0.98	0.23
53	14	19.02	18.76	0.99	0.13
54	14	14.84	14.42	0.97	0.21
55	14	21.44	20.53	0.96	0.45
56	14	17.60	16.48	0.94	0.56
58	14	18.25	16.87	0.92	0.69
59	14	7.95	7.46	0.94	0.24
60	14	10.30	9.51	0.92	0.39
61	14	13.17	12.49	0.95	0.34
62	14	6.52	5.69	0.87	0.42
1	16	9.86	9.07	0.92	0.40
2	16	15.28	14.17	0.93	0.55
3	16	13.06	12.76	0.98	0.15
4	16	20.30	18.64	0.92	0.83
5	16	9.84	8.12	0.83	0.86
6	16	8.91	8.61	0.97	0.15
8	16	16.40	14.74	0.90	0.83
9	16	16.66	15.66	0.94	0.50
11	16	14.75	13.52	0.92	0.61
12	16	16.17	15.78	0.98	0.19
13	16	15.68	14.39	0.92	0.64
14	16	12.73	11.98	0.94	0.38
15	16	15.31	14.49	0.95	0.41
16	16	12.17	11.57	0.95	0.30
17	16	16.62	16.26	0.98	0.18
20	16	15.21	13.19	0.87	1.01
21	16	8.12	7.35	0.91	0.38
22	16	14.18	13.70	0.97	0.24
23	16	10.53	10.00	0.95	0.27
24	16	10.78	10.36	0.96	0.21
1	17	20.19	18.19	0.90	1.00
2	17	14.78	14.78	1.00	0.00
3	17	16.35	18.27	0.89	0.96
4	17	14.24	16.48	0.86	1.12
5	17	19.92	19.92	1.00	0.00
6	17	16.81	16.81	1.00	0.00
7	17	18.04	19.12	0.94	0.54
8	17	15.54	15.54	1.00	0.00
9	17	19.05	19.05	1.00	0.00
10	17	18.72	16.48	0.88	1.12
11	17	18.15	18.15	1.00	0.00
12	17	12.16	12.16	1.00	0.00
13	17	16.11	16.11	1.00	0.00
15	17	18.16	18.16	1.00	0.00
16	17	9.94	9.94	1.00	0.00

17	17	12.79	12.79	1.00	0.00
18	17	26.85	26.80	1.00	0.03
19	17	26.74	26.80	1.00	0.03
20	17	18.80	18.80	1.00	0.00
21	17	15.10	15.10	1.00	0.00
22	17	23.46	23.46	1.00	0.00
23	17	20.79	19.17	0.92	0.81
24	17	21.07	20.93	0.99	0.07
25	17	8.75	8.75	1.00	0.00
26	17	11.36	11.36	1.00	0.00
27	17	16.85	16.85	1.00	0.00
28	17	9.44	9.44	1.00	0.00
29	17	11.77	11.77	1.00	0.00
30	17	20.00	20.00	1.00	0.00
31	17	17.05	17.05	1.00	0.00
32	17	13.95	13.95	1.00	0.00
33	17	15.74	15.74	1.00	0.00
34	17	25.54	25.54	1.00	0.00
35	17	19.43	19.43	1.00	0.00
36	17	13.42	13.42	1.00	0.00
37	17	18.05	18.05	1.00	0.00
38	17	19.77	19.77	1.00	0.00
39	17	20.57	18.30	0.89	1.14
40	17	16.02	18.30	0.88	1.14
41	17	16.86	16.86	1.00	0.00
42	17	16.02	16.02	1.00	0.00
43	17	15.80	15.80	1.00	0.00
44	17	14.46	14.46	1.00	0.00
45	17	21.96	21.96	1.00	0.00
46	17	18.99	18.99	1.00	0.00
47	17	12.58	12.58	1.00	0.00

Appendix 13, Tree Height Data from All Study Areas Collected by Sarawak Forestry Corporation

Region	Study areaID	Sub_Study area	Family	Species	DBH	Height(m)
Sibu	16	B1	Euphorbiaceae	Macaranga triloba	10.2	12
Sibu	16	B1	Dipterocarpaceae	Shorea hopeifolia	24.2	12
Sibu	16	B1	Dipterocarpaceae	Vatica sarawakensis	15.7	14
Sibu	16	B1	Dipterocarpaceae	Shorea parvifolia ssp. parvifolia	20.3	16
Sibu	16	B1	Burseraceae	Santiria laevigata	11.8	14
Sibu	16	B1	Dipterocarpaceae	Shorea hopeifolia	20	18
Sibu	16	B1	Myrtaceae	Syzygium	10.5	8
Sibu	16	B1	Elaeocarpaceae	Elaeocarpus stipularis	42.1	24
Sibu	16	B1	Flacourtiaceae	Homalium	12.3	13
Sibu	16	A	Elaeocarpaceae	Elaeocarpus stipularis	50.9	18
Sibu	16	A	Elaeocarpaceae	Elaeocarpus stipularis	46.9	10
Sibu	16	A	Dipterocarpaceae	Shorea parvifolia ssp. parvifolia	35.5	26
Sibu	16	A	Fagaceae	Lithocarpus	31.3	8
Sibu	16	A	Olacaceae	Ochanostachys amentacea	32.3	25
Sibu	16	A	Fagaceae	Lithocarpus	33	8
Sibu	16	A	Dipterocarpaceae	Shorea parvifolia ssp. velutinata	32.5	19
Sibu	16	B2	Dipterocarpaceae	Shorea parvifolia ssp. parvifolia	29.6	19
Sibu	16	B2	Fagaceae	Lithocarpus	11.2	13
Sibu	16	B2	Moraceae	Artocarpus dadah	12.5	13
Sibu	16	B2	Elaeocarpaceae	Elaeocarpus stipularis	23.8	15
Sibu	16	B2	Theaceae	Adinandra dumosa	23	15
Sibu	16	B2	Theaceae	Adinandra dumosa	30.3	21
Sibu	16	B2	Theaceae	Adinandra dumosa	22.6	18
Sibu	16	B2	Euphorbiaceae	Macaranga beccariana	11.7	14
Sibu	16	B2	Flacourtiaceae	Homalium	14.5	16
Sibu	16	B2	Dipterocarpaceae	Shorea parvifolia ssp. parvifolia	19.8	22
Sibu	16	B2	Theaceae	Adinandra dumosa	17.3	18
Sibu	16	B2	Dipterocarpaceae	Shorea sp.	60	28
Sibu	16	B2	Myristicaceae	Gymnacranthera contracta	16.4	16
Sibu	16	B2	Euphorbiaceae	Pimeleodendron griffithianum	11.1	12
Sibu	16	B2	Myrtaceae	Syzygium	11.6	12
Sibu	16	B2	Dipterocarpaceae	Shorea parvifolia ssp. velutinata	14.1	13
Sibu	16	B2	Dipterocarpaceae	Shorea parvifolia ssp. velutinata	12.9	11
Sibu	16	B2	Dipterocarpaceae	Shorea parvifolia ssp. velutinata	41.9	27
Sibu	16	B2	Dipterocarpaceae	Shorea parvifolia ssp. velutinata	31.8	23
Sibu	01	B1	Dipterocarpaceae	Hopea kerangasensis	18	18
Sibu	01	B1	Euphorbiaceae	Macaranga beccariana	13.4	16
Sibu	01	B1	Annonaceae	Drepananthus carinatus	18.5	15
Sibu	01	B1	Dipterocarpaceae	Dipterocarpus crinitus	23.2	20
Sibu	01	B1	Anacardiaceae	Melanochyla	11.8	14
Sibu	01	B1	Dipterocarpaceae	Shorea hopeifolia	30.2	25
Sibu	01	B1	Euphorbiaceae	Mallotus penangensis	11.8	13
Sibu	01	B1	Dipterocarpaceae	Vatica micrantha	12	13
Sibu	01	B1	Dipterocarpaceae	Shorea parvifolia ssp. velutinata	13.2	15
Sibu	01	B1	Hypericaceae	Cratoxylum arborescens	16.2	18
Sibu	01	B1	Dipterocarpaceae	Shorea parvifolia ssp. velutinata	10.2	12
Sibu	01	B1	Dipterocarpaceae	Vatica micrantha	27.3	25
Sibu	01	B1	Dipterocarpaceae	Shorea hopeifolia	18.4	15
Sibu	01	B1	Dipterocarpaceae	Shorea sp.	40	25
Sibu	01	B1	Clusiaceae	Mammea	13.7	17
Sibu	01	B1	Dipterocarpaceae	Shorea hopeifolia	54.5	32
Sibu	01	B1	Dipterocarpaceae	Vatica micrantha	10.4	12
Sibu	01	B1	Dipterocarpaceae	Shorea parvifolia ssp. velutinata	13.2	16
Sibu	01	A	Dipterocarpaceae	Dipterocarpus crinitus	45.3	28

Sibu	01	A	Anacardiaceae	Melanochyla=5	23.8	15
Sibu	01	A	Dipterocarpaceae	Vatica micrantha	30.5	25
Sibu	01	A	Dipterocarpaceae	Shorea sp.	50	1.5
Sibu	01	A	Myrtaceae	Syzygium	30.4	28
Sibu	01	A	Dipterocarpaceae	Vatica	33.3	28
Sibu	01	A	Myrtaceae	Syzygium=23	34.1	25
Sibu	01	A	Burseraceae	Canarium	40	24
Sibu	01	A	Myrtaceae	Syzygium	31.6	1.6
Sibu	01	B2	Actinidiaceae	Saurauia	12.1	12
Sibu	01	B2	Euphorbiaceae	Macaranga beccariana	13.1	16
Sibu	01	B2	Rutaceae	Melicope	14.1	15
Sibu	01	B2	Dipterocarpaceae	Vatica oblongifolia	13.8	14
Sibu	01	B2	Dipterocarpaceae	Vatica oblongifolia	11.8	13
Sibu	01	B2	Myristicaceae	Knema	18.6	17
Sibu	01	B2	Myrtaceae	Syzygium	13.6	14
Sibu	01	B2	Euphorbiaceae	Blumeodendron kurzii	16.7	15
Sibu	01	B2	Annonaceae	Drepananthus carinatus	20.4	17
Sibu	01	B2	Dipterocarpaceae	Shorea parvifolia ssp. velutinata	12.7	12
Sibu	05	B1	Euphorbiaceae	Glochidion macrostigma	11.1	8
Sibu	05	B1	Annonaceae	Xylopia elliptica	17.7	13
Sibu	05	B1	Clusiaceae	Calophyllum	37.6	18
Sibu	05	B1	Dipterocarpaceae	Vatica micrantha	14.8	15
Sibu	05	B1	Fagaceae	Lithocarpus	16.1	14
Sibu	05	B1	Burseraceae	Santiria	25.6	23
Sibu	05	B1	Dipterocarpaceae	Shorea faguetiana	24.6	25
Sibu	05	B1	Lauraceae	Litsea	15.5	15
Sibu	05	B1	Myrtaceae	Syzygium	19.6	21
Sibu	05	B1	Dipterocarpaceae	Vatica micrantha	25.6	22
Sibu	05	B1	Anisophylleaceae	Anisophyllea corneri	31.4	26
Sibu	05	B1	Myrtaceae	Syzygium=9	19	17
Sibu	05	B1	Euphorbiaceae	Macaranga hosei	17.6	15
Sibu	05	B1	Dipterocarpaceae	Vatica micrantha	12.6	15
Sibu	05	B1	Fagaceae	Lithocarpus blumeanus	21	16
Sibu	05	B1	Fagaceae	Lithocarpus blumeanus	27.3	17
Sibu	05	B1	Flacourtiaceae	Hydnocarpus	24.8	23
Sibu	05	A	Malavaceae	Scaphium macropodum	33.4	16
Sibu	05	A	Dipterocarpaceae	Shorea pinanga	64	29
Sibu	05	A	Dipterocarpaceae	Anisoptera laevis	42.1	28
Sibu	05	A	Myrtaceae	Syzgium=9	41.3	25
Sibu	05	A	Lauraceae	Litsea	58.3	26
Sibu	05	A	Fagaceae	Lithocarpus blumeanus	48.2	26
Sibu	05	A	Lauraceae	Litsea=22	28.4	17
Sibu	05	A	Myrtaceae	Syzygium bankense	23.3	12
Sibu	05	A	Dipterocarpaceae	Vatica micrantha	19.3	22
Sibu	05	A	Malvaceae	Scaphium macropodum	15	18
Sibu	05	A	Myrtaceae	Syzygium=	31.7	22
Sibu	05	A	Fagaceae	Lithocarpus blumeanus	12.3	18
Sibu	05	A	Fagaceae	Lithocarpus blumeanus	13.1	17
Sibu	05	A	Lauraceae	Litsea=	43.5	25
Sibu	05	B2	Dipterocarpaceae	Vatica micrantha	10.2	15
Sibu	05	B2	Lamiaceae	Teijsmanniodendron	31.1	23
Sibu	05	B2	Malvaceae	Scaphium macropodum	27.2	19
Sibu	05	B2	Euphorbiaceae	Macaranga hosei	10.2	15
Sibu	05	B2	Dipterocarpaceae	Shorea parvifolia ssp. parvifolia	37	27
Sibu	14	B1	Fabaceae	Saraca declinata	20.5	15
Sibu	14	B1	Dipterocarpaceae	Shorea pinanga	12.4	12
Sibu	14	B1	Myristicaceae	Knema	15.7	14

Sibu	14	B1	Euphorbiaceae	Macaranga hosei	14.3	15
Sibu	14	B1	Euphorbiaceae	Macaranga hosei	11.3	15
Sibu	14	B1	Euphorbiaceae	Macaranga trachyphylla	14.2	16
Sibu	14	B1	Euphorbiaceae	Macaranga trachyphylla	13.2	15
Sibu	14	B1	Actinidiaceae	Saurauia	12.6	14
Sibu	14	B1	Euphorbiaceae	Macaranga hosei	10.9	15
Sibu	14	A	Olacaceae	Ochanostachys amentacea	32.2	18
Sibu	14	A	Euphorbiaceae	Macaranga hosei	31.6	28
Sibu	14	A	Ebenaceae	Diospyros	37.8	9
Sibu	14	A	Myristicaceae	Knema=3	36.9	22
Sibu	14	A	Dipterocarpaceae	Shorea kunstleri	37.7	25
Sibu	14	A	Anacardiaceae	Semecarpus	39.5	25
Sibu	14	A	Dipterocarpaceae	Shorea parvifolia ssp. parvifolia	35.8	17
Sibu	14	A	Lauraceae	Litsea sp.	30.2	23
Sibu	14	B2	Dipterocarpaceae	Shorea parvistipulata ssp. parvistipulata	45.2	28
Sibu	14	B2	Polygalaceae	Xanthophyllum flavescens	13.8	16
Sibu	14	B2	Myrtaceae	Syzgium	19.1	8
Sibu	14	B2	Dipterocarpaceae	Shorea parvistipulata ssp. parvistipulata	9	21
Sibu	14	B2	Fagaceae	Lithocarpus conocarpus	11.2	12
Sibu	14	B2	Dipterocarpaceae	Shorea parvistipulata ssp. parvistipulata	11.7	14
Sibu	14	B2	Myrtaceae	Syzygium=20	34.8	18
Sibu	14	B2	Dipterocarpaceae	Vatica vinosa	30.9	26
Sibu	14	B2	Dipterocarpaceae	Shorea parvistipulata ssp. parvistipulata	13.5	14
Sibu	14	B2	Lauraceae	Litsea	27.8	25
Sibu	17	B1	Rutaceae	Melicope	17.6	13
Sibu	17	B1	Meliaceae	Aglaia	15.1	14
Sibu	17	B1	Euphorbiaceae	Macaranga hosei	26.6	18
Sibu	17	B1	Euphorbiaceae	Glochidion macrostigma	19.9	21
Sibu	17	B1	Euphorbiaceae	Macaranga hosei	22.5	20
Sibu	17	B1	Flacoutiaceae	Hydnocarpus	17.3	24
Sibu	17	B1	Meliaceae	Aglaia	27.7	24
Sibu	17	B1	Ebenaceae	Diospyros	34.7	26
Sibu	17	B1	Meliaceae	Aglaia	17	14
Sibu	17	B1	Rutaceae	Melicope	13.2	13
Sibu	17	B1	Myrtaceae	Syzygium	10.9	12
Sibu	17	B1	Myrtaceae	Syzygium=11	21.8	16
Sibu	17	B1	Fagaceae	Lithocarpus	26.3	18
Sibu	17	B1	Thymelaeaceae	Gonystylus	12.5	7
Sibu	17	B1	Lythraceae	Duabanga moluccana	23.5	18
Sibu	17	A	Ebenaceae	Diospyros=8	39.5	25
Sibu	17	A	Myrtaceae	Syzygium	31.8	25
Sibu	17	A	Anacardiaceae	Campnosperma squamatum	30.7	25
Sibu	17	A	Sapotaceae	Madhuca	31	22
Sibu	17	A	Myrtaceae	Syzygium oligomyrum	39.7	33
Sibu	17	A	Meliaceae	Aglaia	57	20
Sibu	17	A	Sapindaceae	Nephelium cuspidatum	38.2	28
Sibu	17	A	Dipterocarpaceae	Hopea pachycarpa	41	26
Sibu	17	B2	Olacaceae	Ochanostachys amentacea	34.8	25
Sibu	17	B2	Actinidiaceae	Saurauia	10.7	7
Sibu	17	B2	Lauraceae	Litsea	12.6	10
Sibu	17	B2	Euphorbiaceae	Baccaurea	11.6	12
Sibu	17	B2	Euphorbiaceae	Aporosa	17.8	17
Sibu	17	B2	Euphorbiaceae	Macaranga hosei	18.8	16
Sibu	17	B2	Tiliaceae	Microcos hirsuta	10.4	10

Appendix 14, Canopy Cover of All Capture Points from all Study Areas Collected by Sarawak Forestry Corporation

Region	Study area_ID	Capture point	Canopy Cover
Sibu	01	A1	86%
Sibu	01	A2	87%
Sibu	01	A3	83%
Sibu	01	A4	85%
Sibu	01	A5	89%
Sibu	01	B1	86%
Sibu	01	B2	91%
Sibu	01	B3	87%
Sibu	01	B4	92%
Sibu	01	B5	90%
Sibu	01	C1	90%
Sibu	01	C2	90%
Sibu	01	C3	85%
Sibu	01	C4	93%
Sibu	01	C5	76%
Sibu	05	A1	91%
Sibu	05	A2	87%
Sibu	05	A3	88%
Sibu	05	A4	90%
Sibu	05	A5	86%
Sibu	05	B1	91%
Sibu	05	B2	89%
Sibu	05	B3	92%
Sibu	05	B4	93%
Sibu	05	B5	86%
Sibu	05	C1	91%
Sibu	05	C2	90%
Sibu	05	C3	93%
Sibu	05	C4	92%
Sibu	05	C5	87%
Sibu	14	A1	94%
Sibu	14	A2	95%
Sibu	14	A3	94%
Sibu	14	A4	93%
Sibu	14	A5	90%
Sibu	14	B1	89%
Sibu	14	B2	92%
Sibu	14	B3	92%
Sibu	14	B4	91%
Sibu	14	B5	90%
Sibu	14	C1	85%
Sibu	14	C2	89%
Sibu	14	C3	74%
Sibu	14	C4	78%
Sibu	14	C5	89%
Sibu	16	A1	87%
Sibu	16	A2	83%
Sibu	16	A3	87%
Sibu	16	A4	88%
Sibu	16	A5	84%
Sibu	16	B1	87%

Sibu	16	B2	84%
Sibu	16	B3	85%
Sibu	16	B4	86%
Sibu	16	B5	85%
Sibu	16	C1	85%
Sibu	16	C2	82%
Sibu	16	C3	76%
Sibu	16	C4	85%
Sibu	16	C5	85%
Sibu	17	A1	85%
Sibu	17	A2	83%
Sibu	17	A3	80%
Sibu	17	A4	91%
Sibu	17	A5	85%
Sibu	17	B1	88%
Sibu	17	B2	88%
Sibu	17	B3	89%
Sibu	17	B4	93%
Sibu	17	B5	90%
Sibu	17	C1	92%
Sibu	17	C2	93%
Sibu	17	C3	92%
Sibu	17	C4	92%
Sibu	17	C5	86%

Appendix 15, Model 3 and Manual Data from All Study Areas with Perimeter and Area Information

ID	Study area	Manual Perimeter	M3 Perimeter	Perimeter Accuracy	Stdev. Perimeter	Manual Area	M3 Area	Area Accuracy	Stdev. Area
9	1	15.07	25.36	0.59	5.14	14.30	23.91	0.60	4.80
15	1	15.83	2.57	0.16	6.63	18.36	1.26	0.07	8.55
40	1	15.23	17.89	0.85	1.33	17.52	11.99	0.68	2.77
33	1	17.92	49.26	0.36	15.67	21.56	41.74	0.52	10.09
28	1	18.12	4.98	0.28	6.57	24.72	2.75	0.11	10.98
27	1	18.60	3.54	0.19	7.53	26.38	1.42	0.05	12.48
23	1	18.66	54.12	0.34	17.73	19.63	48.47	0.40	14.42
37	1	19.19	9.33	0.49	4.93	24.64	5.82	0.24	9.41
41	1	19.22	5.50	0.29	6.86	22.90	3.71	0.16	9.59
10	1	20.25	3.93	0.19	8.16	27.97	2.86	0.10	12.56
42	1	21.25	2.74	0.13	9.26	29.26	0.95	0.03	14.16
14	1	22.01	7.80	0.35	7.11	35.53	6.89	0.19	14.32
16	1	22.49	5.36	0.24	8.57	31.30	4.76	0.15	13.27
25	1	23.02	9.59	0.42	6.72	32.66	7.83	0.24	12.42
11	1	23.03	7.93	0.34	7.55	36.19	6.38	0.18	14.90
34	1	22.10	28.63	0.77	3.27	33.17	24.07	0.73	4.55
2	1	24.99	3.60	0.14	10.69	37.55	1.87	0.05	17.84
18	1	25.52	5.98	0.23	9.77	35.52	5.58	0.16	14.97
22	1	26.26	2.93	0.11	11.66	33.82	0.94	0.03	16.44
5	1	26.73	8.65	0.32	9.04	49.30	6.67	0.14	21.32
36	1	23.85	23.37	0.98	0.24	41.82	25.29	0.60	8.26
3	1	27.47	8.45	0.31	9.51	52.44	7.90	0.15	22.27
29	1	29.41	5.40	0.18	12.00	43.72	3.37	0.08	20.17
31	5	8.99	3.63	0.40	2.68	5.59	4.28	0.77	0.65
32	5	8.99	4.61	0.51	2.19	5.79	3.75	0.65	1.02
41	5	14.44	3.49	0.24	5.47	12.68	28.17	0.45	7.75
39	5	14.05	2.76	0.20	5.64	13.21	6.80	0.51	3.21
38	5	14.16	2.42	0.17	5.87	13.78	1.96	0.14	5.91
16	5	17.54	2.72	0.15	7.41	15.70	7.46	0.48	4.12
23	5	15.22	4.68	0.31	5.27	15.77	10.66	0.68	2.55
43	5	24.90	7.10	0.29	8.90	17.33	15.43	0.89	0.95
24	5	15.46	3.11	0.20	6.17	17.53	8.17	0.47	4.68
11	5	16.50	5.04	0.31	5.73	19.25	27.11	0.71	3.93
17	5	18.45	4.12	0.22	7.16	19.52	10.40	0.53	4.56
25	5	18.05	2.67	0.15	7.69	20.43	4.15	0.20	8.14
13	5	16.57	3.92	0.24	6.32	20.35	16.46	0.81	1.95
37	5	20.98	3.18	0.15	8.90	20.92	14.81	0.71	3.05
33	5	18.60	2.46	0.13	8.07	23.11	6.32	0.27	8.40
34	5	20.19	2.66	0.13	8.76	22.40	4.33	0.19	9.04
2	5	20.55	2.41	0.12	9.07	24.72	4.41	0.18	10.16
6	5	23.65	13.36	0.56	5.14	26.52	71.26	0.37	22.37
40	5	22.81	3.91	0.17	9.45	26.69	27.11	0.98	0.21
19	5	22.50	2.67	0.12	9.92	27.28	8.27	0.30	9.50
21	5	25.21	6.91	0.27	9.15	31.67	50.91	0.62	9.62
12	5	20.59	2.87	0.14	8.86	32.05	20.91	0.65	5.57
7	5	22.28	3.84	0.17	9.22	32.49	31.52	0.97	0.48
20	5	24.83	2.98	0.12	10.93	34.58	15.06	0.44	9.76
14	5	24.21	3.26	0.13	10.47	35.37	9.13	0.26	13.12
27	5	25.74	3.20	0.12	11.27	35.51	12.52	0.35	11.50
18	5	24.97	2.44	0.10	11.26	36.34	11.72	0.32	12.31
30	5	26.85	2.96	0.11	11.94	37.59	13.35	0.36	12.12
26	5	26.30	3.06	0.12	11.62	42.55	19.42	0.46	11.56
29	5	27.23	3.25	0.12	11.99	45.99	31.52	0.69	7.24
9	5	29.30	3.47	0.12	12.91	59.08	30.14	0.51	14.47
10	5	31.77	3.36	0.11	14.21	62.35	31.24	0.50	15.56
3	5	35.78	5.35	0.15	15.22	85.42	125.89	0.68	20.23
5	5	46.55	3.77	0.08	21.39	120.96	83.45	0.69	18.76
64	14	11.00	14.31	0.77	1.65	8.10	9.18	0.88	0.54
65	14	12.00	17.37	0.69	2.68	9.60	15.55	0.62	2.97

18	14	12.00	3.43	0.29	4.29	9.10	1.04	0.11	4.03
19	14	11.00	28.47	0.39	8.74	9.90	30.36	0.33	10.23
17	14	12.00	4.93	0.41	3.54	10.00	2.82	0.28	3.59
9	14	12.00	23.32	0.51	5.66	10.00	18.94	0.53	4.47
60	14	12.00	34.67	0.35	11.33	10.00	28.42	0.35	9.21
33	14	13.00	8.88	0.68	2.06	12.00	6.41	0.53	2.80
35	14	14.00	4.35	0.31	4.83	16.00	2.36	0.15	6.82
63	14	15.00	47.90	0.31	16.45	10.00	44.51	0.22	17.25
39	14	16.00	3.50	0.22	6.25	19.00	1.88	0.10	8.56
34	14	17.00	5.65	0.33	5.68	20.00	4.10	0.21	7.95
5	14	18.00	33.35	0.54	7.67	19.00	28.19	0.67	4.59
38	14	18.00	4.24	0.24	6.88	25.00	2.71	0.11	11.14
61	14	17.00	15.30	0.90	0.85	20.00	14.76	0.74	2.62
32	14	19.00	6.25	0.33	6.38	26.00	4.84	0.19	10.58
12	14	20.00	9.46	0.47	5.27	22.00	8.62	0.39	6.69
37	14	18.00	12.08	0.67	2.96	22.00	9.09	0.41	6.45
45	14	18.00	32.90	0.55	7.45	24.00	34.99	0.69	5.49
16	14	22.00	42.31	0.52	10.16	24.00	42.69	0.56	9.34
51	14	21.00	10.01	0.48	5.50	25.00	6.96	0.28	9.02
36	14	21.00	5.27	0.25	7.87	27.00	2.77	0.10	12.12
10	14	22.00	3.13	0.14	9.44	34.00	1.45	0.04	16.27
3	14	23.00	41.22	0.56	9.11	28.00	43.89	0.64	7.94
62	14	23.00	17.54	0.76	2.73	30.00	16.65	0.55	6.68
7	14	29.00	17.32	0.60	5.84	31.00	13.34	0.43	8.83
22	14	29.00	31.65	0.92	1.33	31.00	44.96	0.69	6.98
42	14	23.00	8.81	0.38	7.10	31.00	6.63	0.21	12.18
14	14	23.00	11.48	0.50	5.76	33.00	9.07	0.27	11.96
4	14	23.00	48.81	0.47	12.91	32.00	49.73	0.64	8.86
2	14	25.00	12.87	0.51	6.06	42.00	10.60	0.25	15.70
31	14	25.00	7.82	0.31	8.59	46.00	6.73	0.15	19.64
46	14	22.00	20.42	0.93	0.79	38.00	21.84	0.57	8.08
26	14	30.00	43.75	0.69	6.88	39.00	64.40	0.61	12.70
50	14	26.00	4.65	0.18	10.67	46.00	2.44	0.05	21.78
57	14	26.00	10.81	0.42	7.60	47.00	9.11	0.19	18.95
53	14	25.00	16.91	0.68	4.05	40.00	16.09	0.40	11.95
30	14	24.00	24.33	0.99	0.17	40.00	27.30	0.68	6.35
8	14	30.00	22.49	0.75	3.76	44.00	22.51	0.51	10.75
1	14	28.00	17.38	0.62	5.31	46.00	16.25	0.35	14.88
40	14	26.00	26.02	1.00	0.01	49.00	30.35	0.62	9.33
59	14	31.00	12.83	0.41	9.09	55.00	10.59	0.19	22.21
54	14	31.00	62.37	0.50	15.68	55.00	66.31	0.83	5.66
58	14	32.00	6.36	0.20	12.82	49.00	4.14	0.08	22.43
20	14	34.00	3.62	0.11	15.19	42.00	1.42	0.03	20.29
23	14	34.00	28.06	0.83	2.97	72.00	41.05	0.57	15.47
11	14	37.00	10.38	0.28	13.31	54.00	8.78	0.16	22.61
48	14	36.00	31.62	0.88	2.19	80.00	38.73	0.48	20.64
25	14	39.00	33.47	0.86	2.77	80.00	43.93	0.55	18.04
15	14	41.00	88.71	0.46	23.85	80.00	113.55	0.70	16.78
24	14	37.00	39.98	0.93	1.49	88.00	58.06	0.66	14.97
8	16	14.12	4.40	0.31	4.86	14.94	2.43	0.16	6.26
7	16	14.33	2.82	0.20	5.76	12.78	0.82	0.06	5.98
21	16	16.32	2.48	0.15	6.92	19.84	0.55	0.03	9.64
3	16	16.94	2.90	0.17	7.02	15.94	1.10	0.07	7.42
10	16	17.24	3.73	0.22	6.75	17.86	1.54	0.09	8.16
19	16	17.76	4.14	0.23	6.81	20.51	1.97	0.10	9.27
14	16	17.86	2.73	0.15	7.57	20.24	0.68	0.03	9.78
16	16	19.13	2.83	0.15	8.15	23.93	0.65	0.03	11.64
12	16	19.16	3.62	0.19	7.77	26.78	1.22	0.05	12.78
5	16	19.55	3.89	0.20	7.83	27.23	2.04	0.08	12.59
24	16	19.90	5.02	0.25	7.44	19.93	3.12	0.16	8.41
2	16	20.19	6.34	0.31	6.93	21.85	4.18	0.19	8.83
1	16	22.46	5.11	0.23	8.67	30.39	3.07	0.10	13.66
6	16	24.33	2.59	0.11	10.87	35.95	1.00	0.03	17.48

11	16	25.27	3.56	0.14	10.85	42.68	1.21	0.03	20.74
9	16	28.01	3.60	0.13	12.20	44.37	1.54	0.03	21.42
13	16	28.97	2.96	0.10	13.00	45.60	0.73	0.02	22.43
21	17	6.67	14.20	0.47	3.76	3.15	21.17	0.15	9.01
26	17	8.51	13.72	0.62	2.61	5.14	7.05	0.73	0.96
14	17	8.90	2.43	0.27	3.24	5.64	0.76	0.13	2.44
18	17	15.16	8.12	0.54	3.52	13.63	8.95	0.66	2.34
33	17	13.87	8.49	0.61	2.69	14.67	6.38	0.43	4.14
40	17	14.56	7.47	0.51	3.55	14.86	6.48	0.44	4.19
15	17	16.28	22.64	0.72	3.18	15.15	21.51	0.70	3.18
27	17	24.04	22.83	0.95	0.60	16.46	21.41	0.77	2.47
10	17	16.32	6.73	0.41	4.80	17.35	4.88	0.28	6.23
7	17	22.16	48.38	0.46	13.11	16.96	49.13	0.35	16.09
32	17	18.47	24.51	0.75	3.02	18.05	23.34	0.77	2.65
46	17	18.24	8.27	0.45	4.99	24.29	6.86	0.28	8.71
29	17	17.04	33.51	0.51	8.23	21.63	34.46	0.63	6.42
4	17	19.19	4.42	0.23	7.39	17.89	1.99	0.11	7.95
35	17	18.28	9.80	0.54	4.24	22.05	7.78	0.35	7.13
25	17	20.57	24.96	0.82	2.20	23.46	23.32	0.99	0.07
19	17	21.41	2.97	0.14	9.22	25.38	1.20	0.05	12.09
45	17	21.48	5.98	0.28	7.75	33.48	3.48	0.10	15.00
28	17	19.03	14.72	0.77	2.16	25.36	12.72	0.50	6.32
44	17	18.74	22.96	0.82	2.11	25.42	19.96	0.79	2.73
47	17	19.52	38.40	0.51	9.44	26.76	39.96	0.67	6.60
43	17	22.46	5.12	0.23	8.67	34.65	2.53	0.07	16.06
8	17	23.32	11.78	0.50	5.77	33.38	8.53	0.26	12.43
1	17	22.66	20.08	0.89	1.29	35.79	19.52	0.55	8.13
5	17	43.79	51.56	0.85	3.88	35.79	52.30	0.68	8.26
22	17	25.14	7.64	0.30	8.75	28.18	5.40	0.19	11.39
37	17	23.34	17.93	0.77	2.70	37.97	16.57	0.44	10.70
9	17	25.67	8.51	0.33	8.58	22.60	5.39	0.24	8.61
20	17	25.88	6.98	0.27	9.45	37.35	7.14	0.19	15.10
11	17	24.98	34.87	0.72	4.94	40.76	34.48	0.85	3.14
41	17	25.27	22.54	0.89	1.37	44.74	23.62	0.53	10.56
24	17	33.47	16.33	0.49	8.57	55.28	15.17	0.27	20.06
42	17	34.55	76.22	0.45	20.84	75.39	98.64	0.76	11.63
38	17	45.10	97.92	0.46	26.41	130.50	129.70	0.99	0.40

Appendix 16, Model 4 and Manual Data from All Study Areas with Perimeter and Area Information

ID	Study area	Manual Perimeter	M4 Perimeter	Perimeter Accuracy	Stdev. Perimeter	Manual Area	M4 Area	Area Accuracy	Stdev. Area
9	1	13.62	15.07	0.90	0.72	13.29	14.30	0.93	0.50
23	1	14.18	18.66	0.76	2.24	13.68	19.63	0.70	2.98
15	1	15.95	15.83	0.99	0.06	17.83	18.36	0.97	0.26
40	1	20.91	15.23	0.73	2.84	23.80	17.52	0.74	3.14
18	1	18.44	25.52	0.72	3.54	24.33	35.52	0.68	5.60
17	1	19.88	23.48	0.85	1.80	25.64	36.82	0.70	5.59
28	1	26.76	18.12	0.68	4.32	26.23	24.72	0.94	0.76
41	1	23.95	19.22	0.80	2.36	26.50	22.90	0.86	1.80
10	1	20.69	20.25	0.98	0.22	27.17	27.97	0.97	0.40
31	1	20.70	22.29	0.93	0.80	30.85	36.23	0.85	2.69
29	1	26.12	29.41	0.89	1.64	32.98	43.72	0.75	5.37
14	1	24.46	22.01	0.90	1.22	35.42	35.53	1.00	0.05
39	1	28.41	36.29	0.78	3.94	38.08	60.14	0.63	11.03
32	1	25.98	29.26	0.89	1.64	38.26	58.20	0.66	9.97
30	1	22.91	24.03	0.95	0.56	39.07	44.49	0.88	2.71
38	1	35.21	37.37	0.94	1.08	46.60	59.15	0.79	6.27
25	1	33.75	23.02	0.68	5.36	46.66	32.66	0.70	7.00
39	5	14.05	11.46	0.82	1.29	7.05	6.60	0.94	0.22
6	5	23.65	13.07	0.55	5.29	8.90	10.09	0.88	0.59
17	5	18.45	16.10	0.87	1.18	10.16	15.06	0.67	2.45
32	5	8.99	18.38	0.49	4.69	10.50	8.81	0.84	0.85
27	5	25.74	12.32	0.48	6.71	11.82	8.68	0.73	1.57
2	5	20.55	23.10	0.89	1.27	14.89	18.89	0.79	2.00
34	5	20.19	21.66	0.93	0.74	16.23	23.74	0.68	3.76
8	5	31.84	17.08	0.54	7.38	17.26	15.17	0.88	1.04
11	5	16.50	15.68	0.95	0.41	17.50	11.20	0.64	3.15
24	5	15.46	14.17	0.92	0.65	17.62	12.80	0.73	2.41
7	5	22.28	17.87	0.80	2.21	18.40	19.19	0.96	0.39
33	5	18.60	23.39	0.80	2.39	19.88	20.75	0.96	0.43
3	5	35.78	17.06	0.48	9.36	20.02	19.61	0.98	0.20
22	5	51.03	16.78	0.33	17.12	20.37	16.09	0.79	2.14
42	5	37.43	16.15	0.43	10.64	20.48	13.42	0.65	3.53
29	5	27.23	22.55	0.83	2.34	20.83	20.46	0.98	0.18
21	5	25.21	25.99	0.97	0.39	21.34	29.65	0.72	4.15
9	5	29.30	18.41	0.63	5.44	22.44	18.04	0.80	2.20
5	5	46.55	26.05	0.56	10.25	24.58	31.32	0.78	3.37
10	5	31.77	18.35	0.58	6.71	25.23	22.53	0.89	1.35
38	5	14.16	24.24	0.58	5.04	28.97	23.69	0.82	2.64
64	14	39.00	53.41	0.73	7.21	10.00	11.38	0.88	0.69
62	14	64.00	43.57	0.68	10.21	10.00	7.00	0.70	1.50
8	14	36.00	49.26	0.73	6.63	11.00	10.65	0.97	0.17
26	14	368.00	171.13	0.47	98.43	12.00	16.74	0.72	2.37
38	14	51.00	70.85	0.72	9.93	19.00	18.44	0.97	0.28
5	14	76.00	71.98	0.95	2.01	20.00	16.63	0.83	1.69
33	14	17.00	24.98	0.68	3.99	21.00	30.63	0.69	4.82
60	14	54.00	72.48	0.75	9.24	21.00	20.88	0.99	0.06
11	14	40.00	34.13	0.85	2.94	22.00	15.04	0.68	3.48
36	14	54.00	71.79	0.75	8.89	23.00	22.69	0.99	0.15
37	14	72.00	109.57	0.66	18.79	25.00	21.28	0.85	1.86

31	14	40.00	56.07	0.71	8.03	26.00	23.45	0.90	1.27
50	14	42.00	68.73	0.61	13.37	26.00	32.45	0.80	3.22
35	14	22.00	20.37	0.93	0.81	27.00	24.13	0.89	1.44
9	14	44.00	53.15	0.83	4.57	35.00	31.42	0.90	1.79
52	14	75.00	52.58	0.70	11.21	40.00	30.91	0.77	4.55
29	14	25.00	31.13	0.80	3.07	41.00	45.78	0.90	2.39
39	14	52.00	47.22	0.91	2.39	49.00	43.50	0.89	2.75
53	14	93.00	65.09	0.70	13.96	55.00	35.10	0.64	9.95
55	14	31.00	37.63	0.82	3.31	63.00	71.31	0.88	4.15
40	14	37.00	34.57	0.93	1.21	96.00	71.89	0.75	12.05
7	16	24.52	14.33	0.58	5.10	14.45	12.78	0.88	0.84
8	16	17.67	14.12	0.80	1.78	14.72	14.94	0.99	0.11
3	16	20.49	16.94	0.83	1.77	15.72	15.94	0.99	0.11
16	16	18.14	19.13	0.95	0.50	16.00	23.93	0.67	3.96
19	16	25.62	17.76	0.69	3.93	16.16	20.51	0.79	2.18
2	16	22.04	20.19	0.92	0.92	19.42	21.85	0.89	1.21
11	16	26.07	25.27	0.97	0.40	28.89	42.68	0.68	6.90
33	17	13.87	26.20	0.53	6.17	14.67	23.10	0.64	4.21
27	17	24.04	14.64	0.61	4.70	16.46	11.02	0.67	2.72
10	17	16.32	17.38	0.94	0.53	17.35	16.20	0.93	0.57
29	17	17.04	37.20	0.46	10.08	21.63	29.19	0.74	3.78
35	17	18.28	28.29	0.65	5.01	22.05	21.41	0.97	0.32
28	17	19.03	26.28	0.72	3.62	25.36	20.64	0.81	2.36
44	17	18.74	23.45	0.80	2.35	25.42	18.86	0.74	3.28
45	17	21.48	29.58	0.73	4.05	33.48	37.81	0.89	2.17
43	17	22.46	25.71	0.87	1.62	34.65	22.47	0.65	6.09
1	17	22.66	87.33	0.26	32.34	35.79	47.34	0.76	5.78
37	17	23.34	26.78	0.87	1.72	37.97	25.52	0.67	6.22
36	17	23.29	39.08	0.60	7.90	39.34	44.84	0.88	2.75
23	17	35.12	53.80	0.65	9.34	53.84	52.64	0.98	0.60
24	17	33.47	44.35	0.75	5.44	55.28	38.47	0.70	8.41
42	17	34.55	40.00	0.86	2.72	75.39	73.02	0.97	1.18

Appendix 17, Model 5 and Manual Data from All Study Areas with Perimeter and Area Information

ID	Study area	Manual Perimeter	M5 Perimeter	Perimeter Accuracy	Stdev. Perimeter	Manual Area	M5 Area	Area Accuracy	Stdev. Area
19	1	43.22	19.19	0.44	12.01	51.24	24.64	0.48	13.30
21	1	55.22	36.29	0.66	9.47	91.28	60.14	0.66	15.57
23	1	38.42	19.22	0.50	9.60	56.37	22.90	0.41	16.73
8	1	32.55	28.62	0.88	1.97	38.86	33.03	0.85	2.91
31	1	49.62	37.75	0.76	5.93	79.00	104.88	0.75	12.94
24	1	40.02	21.25	0.53	9.38	67.26	29.26	0.43	19.00
34	1	36.82	20.25	0.55	8.28	65.34	27.97	0.43	18.68
10	1	32.81	18.12	0.55	7.35	46.44	24.72	0.53	10.86
42	1	33.61	25.52	0.76	4.05	42.92	35.52	0.83	3.70
4	1	40.98	26.26	0.64	7.36	52.14	33.82	0.65	9.16
40	1	37.62	22.49	0.60	7.56	58.93	31.30	0.53	13.82
14	1	40.02	29.26	0.73	5.38	53.17	58.20	0.91	2.52
28	1	72.56	60.68	0.84	5.94	158.22	184.95	0.86	13.37
37	1	44.29	34.06	0.77	5.11	70.89	88.39	0.80	8.75
2	1	49.62	46.98	0.95	1.32	80.92	95.28	0.85	7.18

17	1	56.56	40.31	0.71	8.12	123.20	114.90	0.93	4.15
26	5	26.30	52.74	0.50	13.22	42.55	83.66	0.51	20.55
2	5	20.55	38.36	0.54	8.91	24.72	57.47	0.43	16.38
34	5	20.19	35.96	0.56	7.89	22.40	52.37	0.43	14.98
12	5	20.59	33.56	0.61	6.49	32.05	58.11	0.55	13.03
7	5	22.28	35.69	0.62	6.71	32.49	67.05	0.48	17.28
29	5	27.23	43.95	0.62	8.36	45.99	67.05	0.69	10.53
30	5	26.85	45.55	0.59	9.35	37.59	53.00	0.71	7.71
10	5	31.77	36.76	0.86	2.49	62.35	59.39	0.95	1.48
28	5	38.94	30.37	0.78	4.29	63.92	65.78	0.97	0.93
15	5	35.29	39.96	0.88	2.33	72.51	109.84	0.66	18.67
42	5	37.43	46.88	0.80	4.72	77.81	82.38	0.94	2.29
1	5	47.43	43.15	0.91	2.14	148.31	115.59	0.78	16.36
22	5	51.03	37.83	0.74	6.60	97.42	91.96	0.94	2.73
5	5	46.55	56.74	0.82	5.09	120.96	120.70	1.00	0.13
6	5	23.65	34.63	0.68	5.49	26.52	53.00	0.50	13.24
4	5	47.13	47.95	0.98	0.41	150.42	173.70	0.87	11.64
36	5	20.29	27.70	0.73	3.71	17.57	52.37	0.34	17.40
6	14	12.00	30.38	0.39	9.19	8.00	28.13	0.28	10.07
16	14	13.00	31.18	0.42	9.09	10.00	31.65	0.32	10.82
59	14	12.00	23.99	0.50	5.99	11.00	23.66	0.46	6.33
51	14	19.00	42.65	0.45	11.82	25.00	61.80	0.40	18.40
32	14	14.00	29.59	0.47	7.79	12.00	31.33	0.38	9.66
36	14	18.00	39.18	0.46	10.59	23.00	64.26	0.36	20.63
38	14	17.00	33.58	0.51	8.29	19.00	49.87	0.38	15.43
62	14	16.00	31.18	0.51	7.59	10.00	41.56	0.24	15.78
35	14	22.00	39.18	0.56	8.59	27.00	64.26	0.42	18.63
3	14	24.00	41.05	0.58	8.52	29.00	55.84	0.52	13.42
13	14	24.00	40.94	0.59	8.47	33.00	59.20	0.56	13.10
5	14	19.00	30.78	0.62	5.89	20.00	33.89	0.59	6.94
33	14	17.00	31.98	0.53	7.49	21.00	40.92	0.51	9.96
15	14	22.00	36.25	0.61	7.12	25.00	45.61	0.55	10.30
61	14	24.00	34.78	0.69	5.39	30.00	50.03	0.60	10.01
60	14	18.00	24.79	0.73	3.39	21.00	27.81	0.76	3.41
44	14	19.00	28.79	0.66	4.89	25.00	35.80	0.70	5.40
19	14	27.00	43.00	0.63	8.00	50.00	72.18	0.69	11.09
37	14	18.00	23.99	0.75	2.99	25.00	23.34	0.93	0.83
2	14	26.00	39.98	0.65	6.99	43.00	64.73	0.66	10.87
4	14	23.00	28.39	0.81	2.69	32.00	36.92	0.87	2.46
20	14	35.00	49.04	0.71	7.02	43.00	84.61	0.51	20.80
40	14	37.00	54.37	0.68	8.69	96.00	117.00	0.82	10.50
23	14	38.00	54.91	0.69	8.45	89.00	122.97	0.72	16.98
9	14	22.00	35.98	0.61	6.99	35.00	45.71	0.77	5.36
47	14	36.00	51.17	0.70	7.59	80.00	104.85	0.76	12.43
45	14	23.00	27.99	0.82	2.49	39.00	33.89	0.87	2.56
52	14	25.00	43.18	0.58	9.09	40.00	58.02	0.69	9.01
25	14	31.00	32.38	0.96	0.69	40.00	53.39	0.75	6.69
7	14	29.50	38.38	0.77	4.44	38.50	58.74	0.66	10.12
30	14	26.00	43.98	0.59	8.99	47.00	61.06	0.77	7.03
1	14	29.00	30.38	0.95	0.69	47.00	34.65	0.74	6.17
56	14	28.67	42.82	0.67	7.08	48.33	59.89	0.81	5.78
53	14	31.00	46.38	0.67	7.69	55.00	65.64	0.84	5.32
58	14	31.00	37.10	0.84	3.05	55.00	47.70	0.87	3.65
10	14	38.00	36.78	0.97	0.61	55.00	52.11	0.95	1.45
55	14	31.00	46.38	0.67	7.69	63.00	63.94	0.99	0.47
54	14	36.00	50.53	0.71	7.27	73.00	91.43	0.80	9.21
22	14	34.00	43.98	0.77	4.99	73.00	83.76	0.87	5.38
46	14	38.00	44.14	0.86	3.07	76.00	79.92	0.95	1.96
14	14	42.00	40.51	0.96	0.74	80.00	62.12	0.78	8.94
27	14	39.00	63.17	0.62	12.08	88.00	105.81	0.83	8.91
24	14	40.00	41.90	0.95	0.95	81.00	53.83	0.66	13.58
43	14	38.00	45.42	0.84	3.71	90.00	76.85	0.85	6.57
42	14	41.00	44.78	0.92	1.89	98.00	79.60	0.81	9.20

10	16	17.86	74.56	0.24	28.35	17.24	48.03	0.36	15.40
12	16	26.78	69.86	0.38	21.54	19.16	44.03	0.44	12.43
17	16	47.04	119.85	0.39	36.40	32.21	57.64	0.56	12.72
16	16	23.93	57.89	0.41	16.98	19.13	42.70	0.45	11.78
22	16	49.58	108.63	0.46	29.53	27.03	52.84	0.51	12.91
8	16	14.94	41.02	0.36	13.04	14.12	33.62	0.42	9.75
21	16	19.84	43.97	0.45	12.07	16.32	35.22	0.46	9.45
19	16	20.51	39.31	0.52	9.40	17.76	28.82	0.62	5.53
14	16	20.24	43.20	0.47	11.48	17.86	32.66	0.55	7.40
24	16	19.93	55.12	0.36	17.59	19.90	33.09	0.60	6.59
9	16	44.37	74.56	0.60	15.09	28.01	48.03	0.58	10.01
6	16	35.95	63.45	0.57	13.75	24.33	42.43	0.57	9.05
7	16	12.78	16.98	0.75	2.10	14.33	20.01	0.72	2.84
3	16	15.94	17.62	0.90	0.84	16.94	20.81	0.81	1.94
5	16	27.23	39.31	0.69	6.04	19.55	28.82	0.68	4.64
1	16	30.39	49.35	0.62	9.48	22.46	32.82	0.68	5.18
11	16	42.68	21.92	0.51	10.38	25.27	22.74	0.90	1.27
13	16	45.60	30.92	0.68	7.34	28.97	29.62	0.98	0.33
18	16	68.26	35.63	0.52	16.31	37.35	30.74	0.82	3.30
20	16	98.45	75.47	0.77	11.49	41.77	41.23	0.99	0.27
4	16	101.26	87.48	0.86	6.89	41.81	46.43	0.90	2.31
23	16	58.96	51.55	0.87	3.71	43.24	33.85	0.78	4.69
15	16	100.19	98.06	0.98	1.07	45.93	52.84	0.87	3.45
3	17	13.60	38.35	0.35	12.38	10.11	51.49	0.20	20.69
26	17	8.51	20.24	0.42	5.87	5.14	15.96	0.32	5.41
14	17	8.90	12.98	0.69	2.04	5.64	9.81	0.57	2.09
2	17	12.62	34.09	0.37	10.73	10.36	47.87	0.22	18.75
31	17	13.80	36.22	0.38	11.21	12.23	45.32	0.27	16.54
33	17	13.87	35.55	0.39	10.84	14.67	47.71	0.31	16.52
45	17	21.48	51.93	0.41	15.22	33.48	74.36	0.45	20.44
47	17	19.52	46.34	0.42	13.41	26.76	65.74	0.41	19.49
46	17	18.24	43.14	0.42	12.45	24.29	65.74	0.37	20.73
17	17	10.59	23.97	0.44	6.69	7.71	28.08	0.27	10.19
10	17	16.32	35.15	0.46	9.42	17.35	51.70	0.34	17.17
35	17	18.28	35.15	0.52	8.44	22.05	53.61	0.41	15.78
23	17	35.12	19.17	0.55	7.98	53.84	19.52	0.36	17.16
25	17	20.57	35.15	0.59	7.29	23.46	53.61	0.44	15.08
43	17	22.46	37.28	0.60	7.41	34.65	62.55	0.55	13.95
41	17	25.27	39.95	0.63	7.34	44.74	78.51	0.57	16.88
6	17	27.38	42.50	0.64	7.56	26.37	57.06	0.46	15.35
28	17	19.03	34.09	0.56	7.53	25.36	42.76	0.59	8.70
9	17	25.67	36.75	0.70	5.54	22.60	46.59	0.49	11.99
37	17	23.34	16.78	0.72	3.28	37.97	19.47	0.51	9.25
27	17	24.04	30.89	0.78	3.43	16.46	37.02	0.44	10.28
5	17	43.79	49.53	0.88	2.87	35.79	68.93	0.52	16.57
7	17	22.16	18.38	0.83	1.89	16.96	21.86	0.78	2.45
39	17	35.96	38.35	0.94	1.19	95.73	57.60	0.60	19.06
32	17	18.47	23.97	0.77	2.75	18.05	26.81	0.67	4.38
29	17	17.04	15.38	0.90	0.83	21.63	14.68	0.68	3.47
44	17	18.74	30.89	0.61	6.07	25.42	32.55	0.78	3.57
8	17	23.32	33.16	0.70	4.92	33.38	41.01	0.81	3.81
1	17	22.66	27.16	0.83	2.25	35.79	26.81	0.75	4.49
11	17	24.98	30.04	0.83	2.53	40.76	34.72	0.85	3.02
24	17	33.47	32.76	0.98	0.36	55.28	41.81	0.76	6.74
42	17	34.55	33.55	0.97	0.50	75.39	45.48	0.60	14.96
34	17	29.81	35.95	0.83	3.07	58.70	57.76	0.98	0.47
16	17	39.29	37.19	0.95	1.05	78.62	60.17	0.77	9.22
30	17	40.00	37.15	0.93	1.43	79.95	56.81	0.71	11.57

Appendix 18, Field Measured Height Data Collected by Sarawak Forestry Corporation

Study areaID	Family	Species	DBH	Height_com(m)	Height(m)
16	Euphorbiaceae	Macaranga triloba	10.2	9	12
16	Dipterocarpaceae	Shorea hopeifolia	24.2	3	12
16	Dipterocarpaceae	Vatica sarawakensis	15.7	4	14
16	Dipterocarpaceae	Shorea parvifolia ssp. parvifolia	20.3	9	16
16	Burseraceae	Santiria laevigata	11.8	7	14
16	Dipterocarpaceae	Shorea hopeifolia	20	11	18
16	Myrtaceae	Syzygium	10.5	2	8
16	Elaeocarpaceae	Elaeocarpus stipularis	42.1	15	24
16	Flacourtiaceae	Homalium	12.3	9	13
16	Elaeocarpaceae	Elaeocarpus stipularis	50.9	7	18
16	Elaeocarpaceae	Elaeocarpus stipularis	46.9	2.5	10
16	Dipterocarpaceae	Shorea parvifolia ssp. parvifolia	35.5	17	26
16	Fagaceae	Lithocarpus	31.3	8	8
16	Olacaceae	Ochanostachys amentacea	32.3	14	25
16	Fagaceae	Lithocarpus	33	8	8
16	Dipterocarpaceae	Shorea parvifolia ssp. velutinata	32.5	12	19
16	Dipterocarpaceae	Shorea parvifolia ssp. parvifolia	29.6	16	19
16	Fagaceae	Lithocarpus	11.2	7	13
16	Moraceae	Artocarpus dadah	12.5	6	13
16	Elaeocarpaceae	Elaeocarpus stipularis	23.8	4	15
16	Theaceae	Adinandra dumosa	23	9	15
16	Theaceae	Adinandra dumosa	30.3	10	21
16	Theaceae	Adinandra dumosa	22.6	12	18
16	Euphorbiaceae	Macaranga beccariana	11.7	8	14
16	Flacourtiaceae	Homalium	14.5	9	16
16	Dipterocarpaceae	Shorea parvifolia ssp. parvifolia	19.8	16	22
16	Theaceae	Adinandra dumosa	17.3	9	18
16	Dipterocarpaceae	Shorea sp.	60	22	28
16	Myristicaceae	Gymnacranthera contracta	16.4	5	16
16	Euphorbiaceae	Pimeleodendron griffithianum	11.1	7	12
16	Myrtaceae	Syzygium	11.6	8	12
16	Dipterocarpaceae	Shorea parvifolia ssp. velutinata	14.1	10	13
16	Dipterocarpaceae	Shorea parvifolia ssp. velutinata	12.9	9	11
16	Dipterocarpaceae	Shorea parvifolia ssp. velutinata	41.9	7	27
16	Dipterocarpaceae	Shorea parvifolia ssp. velutinata	31.8	11	23
01	Dipterocarpaceae	Hopea kerangasensis	18	9	18
01	Euphorbiaceae	Macaranga beccariana	13.4	10	16
01	Annonaceae	Drepananthus carinatus	18.5	9	15
01	Dipterocarpaceae	Dipterocarpus crinitus	23.2	15	20
01	Anacardiaceae	Melanochyla	11.8	7	14
01	Dipterocarpaceae	Shorea hopeifolia	30.2	17	25
01	Euphorbiaceae	Mallotus penangensis	11.8	9	13
01	Dipterocarpaceae	Vatica micrantha	12	10	13
01	Dipterocarpaceae	Shorea parvifolia ssp. velutinata	13.2	9	15
01	Hypericaceae	Cratoxylum arborescens	16.2	10	18
01	Dipterocarpaceae	Shorea parvifolia ssp. velutinata	10.2	9	12
01	Dipterocarpaceae	Vatica micrantha	27.3	25	25
01	Dipterocarpaceae	Shorea hopeifolia	18.4	10	15
01	Dipterocarpaceae	Shorea sp.	40		25
01	Clusiaceae	Mammea	13.7	10	17
01	Dipterocarpaceae	Shorea hopeifolia	54.5	20	32
01	Dipterocarpaceae	Vatica micrantha	10.4	7	12
01	Dipterocarpaceae	Shorea parvifolia ssp. velutinata	13.2	10	16
01	Dipterocarpaceae	Dipterocarpus crinitus	45.3	18	28
01	Anacardiaceae	Melanochyla=5	23.8	4	15
01	Dipterocarpaceae	Vatica micrantha	30.5	15	25
01	Dipterocarpaceae	Shorea sp.	50		1.5
01	Myrtaceae	Syzygium	30.4	19	28
01	Dipterocarpaceae	Vatica	33.3	21	28
01	Myrtaceae	Syzygium=23	34.1	18	25

01	Burseraceae	Canarium	40	12	24
01	Myrtaceae	Syzygium	31.6		1.6
01	Actinidiaceae	Saurauia	12.1	7	12
01	Euphorbiaceae	Macaranga beccariana	13.1	8	16
01	Rutaceae	Melicope	14.1	9	15
01	Dipterocarpaceae	Vatica oblongifolia	13.8	4	14
01	Dipterocarpaceae	Vatica oblongifolia	11.8	9	13
01	Myristicaceae	Knema	18.6	14	17
01	Myrtaceae	Syzygium	13.6	9	14
01	Euphorbiaceae	Blumeodendron kurzii	16.7	8	15
01	Annonaceae	Drepananthus carinatus	20.4	11	17
01	Dipterocarpaceae	Shorea parvifolia ssp. velutinata	12.7	8	12
05	Euphorbiaceae	Glochidion macrostigma	11.1	5	8
05	Annonaceae	Xylopia elliptica	17.7	9	13
05	Clusiaceae	Calophyllum	37.6	12	18
05	Dipterocarpaceae	Vatica micrantha	14.8	8	15
05	Fagaceae	Lithocarpus	16.1	5	14
05	Burseraceae	Santiria	25.6	16	23
05	Dipterocarpaceae	Shorea faguetiana	24.6	17	25
05	Lauraceae	Litsea	15.5	9	15
05	Myrtaceae	Syzygium	19.6	17	21
05	Dipterocarpaceae	Vatica micrantha	25.6	16	22
05	Anisophylleaceae	Anisophyllea corneri	31.4	19	26
05	Myrtaceae	Syzygium=9	19	8	17
05	Euphorbiaceae	Macaranga hosei	17.6	10	15
05	Dipterocarpaceae	Vatica micrantha	12.6	9	15
05	Fagaceae	Lithocarpus blumeanus	21	5	16
05	Fagaceae	Lithocarpus blumeanus	27.3	8	17
05	Flacourtiaceae	Hydnocarpus	24.8	15	23
05	Malavaceae	Scaphium macropodum	33.4	12	16
05	Dipterocarpaceae	Shorea pinanga	64	20	29
05	Dipterocarpaceae	Anisoptera laevis	42.1	19	28
05	Myrtaceae	Syzgium=9	41.3	17	25
05	Lauraceae	Litsea	58.3	16	26
05	Fagaceae	Lithocarpus blumeanus	48.2	16	26
05	Lauraceae	Litsea=22	28.4	9	17
05	Myrtaceae	Syzygium bankense	23.3	7	12
05	Dipterocarpaceae	Vatica micrantha	19.3	16	22
05	Malvaceae	Scaphium macropodum	15	11	18
05	Myrtaceae	Syzygium=	31.7	16	22
05	Fagaceae	Lithocarpus blumeanus	12.3	11	18
05	Fagaceae	Lithocarpus blumeanus	13.1	10	17
05	Lauraceae	Litsea=	43.5	15	25
05	Dipterocarpaceae	Vatica micrantha	10.2	10	15
05	Lamiaceae	Teijsmanniodendron	31.1	16	23
05	Malvaceae	Scaphium macropodum	27.2	12	19
05	Euphorbiaceae	Macaranga hosei	10.2	9	15
05	Dipterocarpaceae	Shorea parvifolia ssp. parvifolia	37	18	27
14	Fabaceae	Saraca declinata	20.5	10	15
14	Dipterocarpaceae	Shorea pinanga	12.4	9	12
14	Myristicaceae	Knema	15.7	8	14
14	Euphorbiaceae	Macaranga hosei	14.3	9	15
14	Euphorbiaceae	Macaranga hosei	11.3	9	15
14	Euphorbiaceae	Macaranga trachyphylla	14.2	10	16
14	Euphorbiaceae	Macaranga trachyphylla	13.2	9	15
14	Actinidiaceae	Saurauia	12.6	9	14
14	Euphorbiaceae	Macaranga hosei	10.9	8	15
914	Olacaceae	Ochanostachys amentacea	32.2	12	18
14	Euphorbiaceae	Macaranga hosei	31.6	14	28
14	Ebenaceae	Diospyros	37.8	6	9
14	Myristicaceae	Knema=3	36.9	17	22
14	Dipterocarpaceae	Shorea kunstleri	37.7	18	25
14	Anacardiaceae	Semecarpus	39.5	17	25

14	Dipterocarpaceae	Shorea parvifolia ssp. parvifolia	35.8	20	17
14	Lauraceae	Litsea sp.	30.2	17	23
14	Dipterocarpaceae	Shorea parvistipulata ssp. parvistipulata	45.2	20	28
14	Polygalaceae	Xanthophyllum flavescens	13.8	11	16
14	Myrtaceae	Syzgium	19.1	3	8
14	Dipterocarpaceae	Shorea parvistipulata ssp. parvistipulata	9	13	21
14	Fagaceae	Lithocarpus conocarpus	11.2	8	12
14	Dipterocarpaceae	Shorea parvistipulata ssp. parvistipulata	11.7	9	14
14	Myrtaceae	Syzygium=20	34.8	9	18
14	Dipterocarpaceae	Vatica vinosa	30.9	17	26
14	Dipterocarpaceae	Shorea parvistipulata ssp. parvistipulata	13.5	9	14
14	Lauraceae	Litsea	27.8	16	25
17	Rutaceae	Melicope	17.6	12	13
17	Meliaceae	Aglaia	15.1	10	14
17	Euphorbiaceae	Macaranga hosei	26.6	16	18
17	Euphorbiaceae	Glochidion macrostigma	19.9	15	21
17	Euphorbiaceae	Macaranga hosei	22.5	7	20
17	Flacoutiaceae	Hydnocarpus	17.3	7	24
17	Meliaceae	Aglaia	27.7	18	24
17	Ebenaceae	Diospyros	34.7	17	26
17	Meliaceae	Aglaia	17	9	14
17	Rutaceae	Melicope	13.2	9	13
17	Myrtaceae	Syzygium	10.9	8	12
17	Myrtaceae	Syzygium=11	21.8	9	16
17	Fagaceae	Lithocarpus	26.3	10	18
17	Thymelaeaceae	Gonystylus	12.5	4	7
17	Lythraceae	Duabanga moluccana	23.5	10	18
17	Ebenaceae	Diospyros=8	39.5	18	25
17	Myrtaceae	Syzygium	31.8	17	25
17	Anacardiaceae	Campnosperma squamatum	30.7	16	25
17	Sapotaceae	Madhuca	31	14	22
17	Myrtaceae	Syzygium oligomyrum	39.7	18	33
17	Meliaceae	Aglaia	57	15	20
17	Sapindaceae	Nephelium cuspidatum	38.2	20	28
17	Dipterocarpaceae	Hopea pachycarpa	41	16	26
17	Olacaceae	Ochanostachys amentacea	34.8	15	25
17	Actinidiaceae	Saurauia	10.7	6	7
17	Lauraceae	Litsea	12.6	6	10
17	Euphorbiaceae	Baccaurea	11.6	9	12
17	Euphorbiaceae	Aporosa	17.8	11	17
17	Euphorbiaceae	Macaranga hosei	18.8	10	16
17	Tiliaceae	Microcos hirsuta	10.4	4	10