

Centre for Geo-Information

Thesis Report GIRS-2017-05

---

# **ABOVE GROUND BIOMASS ESTIMATION IN PALM TREES USING TERRESTRIAL LiDAR AND TREE MODELLING**

Adriana Careli Caballero Rodríguez

14<sup>th</sup> March 2017



**WAGENINGEN**  
UNIVERSITY & RESEARCH



# **Above ground biomass estimation in palm trees using Terrestrial LiDAR and tree modelling**

Adriana Careli Caballero Rodríguez

Registration number 88 07 15 154 020

## Supervisors:

MSc. Alvaro Iván Lau Sarmiento

Dr. Harm Bartholomeus

A thesis submitted in partial fulfilment of the degree of Master of Science  
at Wageningen University and Research Centre,  
The Netherlands.

14<sup>th</sup> March 2017

Wageningen, the Netherlands

Thesis code number: GRS-80436  
Thesis Report: GIRS-2017-05  
Wageningen University and Research Centre  
Laboratory of Geo-Information Science and Remote Sensing



# Foreword

The use of LiDAR point clouds in forest management has become more common due to its accuracy and repeatability of analysis. This remote sensing technique in combination with other methods has contributed to obtain different quantitative estimates of tropical forests characteristics such as tree volume, biomass, gap fraction, etc. Specially, tropical forests contain most of the world's terrestrial biodiversity and are considered as carbon stores. However, forest deforestation and degradation have contributed to the increase of greenhouse gases emissions, and loss of forest extension and biodiversity. Thus, these quantitative estimates as part of forest management contributes to address forest deforestation and degradation.

Therefore, I chose this topic to conduct my master thesis project, motivated by my interest and enjoy of LiDAR, and to propose a method to calculate above ground biomass of two palm species from the Peruvian amazon without having reference data. At the same time, I aimed to contribute in the global research of REDD+ to mitigate the climate change. Certainly, this research helped me to improve my knowledge in LiDAR and forestry as a beginning of future projects in this research line.

This research was supported by Wageningen University & Research, which provided the work space and equipment, and software. In collaboration with the Center for International Forestry Research (CIFOR), which provided the field work data and specific knowledge support on peat swamp forest, palm trees, allometric equations and above ground biomass. I am sure this research is another step of the remote sensing application in the improvement of forest management and REDD+ mechanism.

14<sup>th</sup> March 2017

Adriana Careli Caballero Rodriguez

## Acknowledgements

I would first like to express my gratitude to my main supervisor MSc. Alvaro Lau for his support, guidance, tolerance, time, funny moments and friendship along the process of this master thesis. I also would like to thank to my second supervisor Dr. Harm Bartholomeus, for his useful remarks and advice to improve this research. Moreover, I thank to Kristell Hergoualc'h, who gave me accurate feedback to start this research and for her specific comments regarding palm trees and allometric equations. I also thank to the expert Rosa Goodman, for her quick responses and key inputs about allometric equations.

I would also like to thank to the Center for International Forestry Research (CIFOR) for the permission to use the field inventory and TLS point clouds to carry out this study. Moreover, I am grateful with Alvaro Lau and Jose Gonzalez to organize their schedule and share the use of the powerful PC to process the point clouds. Furthermore, without the financial support of the Consejo Nacional de Ciencia y Tecnología (CONACYT) which offered me a scholarship to study in Wageningen University & Research, this second year of master would not have been possible.

Furthermore, I like to thank my colleagues who helped me with my sensitivity analysis test. Even though they were also busy with their thesis, they accepted to shared their time and cooperate. I also would like to thank to the other colleagues who accepted the invitation to participate, but due to the time incompatibility there were no chance to do the test.

I would also like to express my love and gratitude to my parents Lourdes Rodríguez and Antonio Caballero, who encourage me to not give up and supported me every day to finish this project. I would also like to thank to my boyfriend Angel Marquez who always supported me with love, guidance, knowledge and advice together with happy moments and tolerance throughout this thesis.

Finally, I thank to my family and friends from Mexico, who even with the distance and different time zone always supported me and sent me their good vibes. I also thank to my new friends I met in this University and always had a smile for me and cheer me up when I felt a bit lost in this thesis journey.

## Abstract

Above ground biomass (AGB) is an indicator in tropical forests that helps to determine the quantity of carbon stored in forests to understand the global carbon cycle situation. Particularly, the peat swamp forest, a type of tropical forest ecosystems, stores a huge amount of carbon due to its waterlogged anaerobic condition which influences the formation of layers of peat that retains the carbon. But, its degradation and deforestation, caused by social and economic importance of the fruit of a main palm tree species, contributes to climate change by an increment of greenhouse gases emissions to the atmosphere.

Even by the structural complexity of these ecosystems, it has been confirmed that terrestrial laser scanning (TLS) is an efficient and non-destructive technique that produces detailed point clouds. TLS in combination with quantitative structure modelling allows the reconstruction of accurate 3D structure models of individual trees. A large number of 3D models were visually assessed to identify which Quantitative Structure Models (QSM) parameters rendered the best 3D models. Then, the volume was calculated using these models, which was multiplied by wood density (WD) to estimate AGB.

This study is pioneering in the AGB estimate from 3D QSM of two species of palms, *Mauritia flexuosa* and *Mauritiella armata*, characteristic of peat swamp forest in the Peruvian amazon. AGB of palm trees was also estimated using allometric equations to compare the outcomes with the TLS based models. Whence, the AGB from QSM volume multiplied by mean WD of palms in the tropic region of Global Wood Density Database (GWDD) in comparison with AGB from allometric equations using TLS stem height, presented higher differences in *Mauritiella*. However, the correlation coefficient for *Mauritia* was 0.692 and 0.890 for *Mauritiella*, due to its similar trend in AGB estimates. Simultaneously, the AGB outcomes from allometric equations could not be correlated with AGB from Goodman et al. (2013) due to the lack of Goodman values. But, visually compared the AGB outcomes showed high likeness with Goodman et al. (2013) AGB results.

**Keywords:** *LiDAR, quantitative structure model, above ground biomass, Mauritia flexuosa, Mauritiella armata, allometric equations*



# Table of contents

FOREWORD .....	V
ACKNOWLEDGEMENTS .....	VI
ABSTRACT .....	VII
LIST OF FIGURES .....	X
LIST OF TABLES .....	XI
LIST OF EQUATIONS .....	XI
LIST OF APPENDICES .....	XI
NOMENCLATURE .....	XIII
<b>1. INTRODUCTION .....</b>	<b>1</b>
1.1 CONTEXT AND BACKGROUND .....	1
1.2 PROBLEM DEFINITION .....	4
<b>2. RESEARCH OBJECTIVE AND RESEARCH QUESTIONS.....</b>	<b>6</b>
<b>3. MATERIALS .....</b>	<b>7</b>
3.1 STUDY AREA .....	7
3.2 DATA ACQUISITION .....	8
3.3 SOFTWARE .....	9
<b>4. METHODOLOGY.....</b>	<b>10</b>
4.1 PRE-PROCESSING .....	11
4.2 PROCESSING .....	11
4.2.1 <i>Tree extraction</i> .....	12
4.2.2 <i>Quantitative Structure Model (QSM)</i> .....	15
4.2.3 <i>Sensitivity Analysis</i> .....	18
4.2.4 <i>AGB from QSM</i> .....	21
4.2.5 <i>AGB from allometric equations</i> .....	23
4.3 ANALYSIS .....	24
4.3.1 <i>Sensitivity Analysis tests</i> .....	25
4.3.2 <i>Comparison of field and TLS data</i> .....	25
<b>5. RESULTS .....</b>	<b>27</b>
5.1 TREE EXTRACTION .....	27
5.2 QUANTITATIVE STRUCTURE MODEL (QSM) .....	28
5.3 SENSITIVITY ANALYSIS .....	29
5.4 COMPARISON OF AGB ESTIMATES FROM QSM USING DIFFERENT WOOD DENSITIES .....	31
5.5 COMPARISON OF AGB FROM ALLOMETRIC EQUATIONS AND WITH GOODMAN ET AL. (2013) RESULTS .....	32
5.6 COMPARISON BETWEEN AGB ESTIMATES FROM QSM AND ALLOMETRIC EQUATIONS .....	35
<b>6. DISCUSSION.....</b>	<b>39</b>
6.1 DIFFICULTIES IN MANUAL TREE EXTRACTION .....	39
6.2 SIGNIFICANT ELEMENTS TO ENHANCE THE QUANTITATIVE STRUCTURE MODEL.....	40
6.3 SUBJECTIVITY OF VISUAL SENSITIVITY ANALYSIS.....	41
6.4 MISSING ELEMENTS TO ESTIMATE ACCURATELY AGB FROM QSM AND VALIDATION .....	42
6.5 DISCREPANCY IN FIELD AND TLS MEASUREMENTS USED IN ALLOMETRIC EQUATIONS TO ESTIMATE AGB.....	43
<b>7. CONCLUSIONS .....</b>	<b>44</b>
<b>8. REFERENCES .....</b>	<b>45</b>
<b>9. APPENDICES .....</b>	<b>50</b>

# List of Figures

<i>Figure 1. Crown of Mauritia flexuosa (Source Kahn et al., 1993)</i> .....	3
<i>Figure 2. Location of study area (source (GEOSUR, n.d.))</i> .....	7
<i>Figure 3. Grid of scans per plot</i> .....	8
<i>Figure 4. Methodology flow diagram</i> .....	10
<i>Figure 5. Co-registered point cloud of Plot 1 after multi station adjustment</i> .....	11
<i>Figure 6. Palm tree found in point cloud using X, Y, Z coordinates, angle and distance to centre scan. a) Top view, b) Front view</i> .....	13
<i>Figure 7. Extracted tree point cloud of Mauritia flexuosa using RiScan Pro</i> .....	14
<i>Figure 8. Point cloud of the 20 extracted palm trees</i> .....	14
<i>Figure 9. 3D QSM palm tree (Mauritia). a) Figure result from MATLAB, b) 3D figure visualized in Cloud Compare</i> .....	18
<i>Figure 10. Sensitivity analysis of Mauritia flexuosa. Left box presents the grade and right box shows the PatchDiam2Min value. Red circles mark the main aspects considered to define the grade</i> .....	20
<i>Figure 11. Sensitivity analysis of Mauritiella armata. Left box presents the grade and right box shows the PatchDiam2Min value. Yellow circles mark the main aspects considered to define the grade</i> .....	20
<i>Figure 12. Display of Mauritiella QSM in Cloud Compare showing all the branch orders</i> .....	21
<i>Figure 13. Displays of palms' QSMs branch order that covers the trunk. a) Mauritia, b) Mauritiella</i> .....	22
<i>Figure 14. Point showing the Z value at the top of the stem in TLS point cloud. a) Mauritia, b) Mauritiella</i> ...	26
<i>Figure 15. Point showing the ground point and Z value in TLS point cloud</i> .....	26
<i>Figure 16. Examples of extracted palm trees per species. a), b) Mauritia and c), d) Mauritiella</i> .....	27
<i>Figure 17. Examples of QSMs. Upper images represent good stem model and below images show less quality stem model</i> .....	28
<i>Figure 18. AGB estimates with QSM for Mauritia flexuosa. a) Comparison of AGB in bars showing both WDs, b) Difference between both AGB represented with error bars</i> .....	31
<i>Figure 19. AGB estimates with QSM for Mauritiella armata. a) Comparison of AGB in bars showing both WDs, b) Difference between both AGB represented with error bars</i> .....	32
<i>Figure 20. Comparison of AGB from allometric equations using Field and TLS data: a) Mauritia flexuosa, b) Mauritiella armata</i> .....	33
<i>Figure 21. Correlation of AGB from allometric equations: a) Mauritia flexuosa, b) Mauritiella armata</i> .....	33
<i>Figure 22. Comparison of AGB estimates using allometric equations with Goodman et al. (2013) AGB results. Both graphs represent the relation between stem height and AGB.</i> .....	34
<i>Figure 23. Goodman et al. (2013) AGB estimations for Mauritia and Mauritiella</i> .....	35
<i>Figure 24. Mauritia flexuosa: Comparison of AGB estimates from QSM and allometric equations</i> .....	36
<i>Figure 25. Mauritiella armata: Comparison of AGB estimates from QSM and allometric equations</i> .....	36
<i>Figure 26. Mauritia flexuosa: Correlation of best AGB estimates from QSM and allometric equations</i> .....	37
<i>Figure 27. Mauritiella armata: Correlation of best AGB estimates from QSM and allometric equations</i> .....	37
<i>Figure 28. Display of point cloud at 1 meter of height. Each circle is a tree and its diameter can be measured with the rule tool.</i> .....	40

## List of Tables

<i>Table 1. Software used: name and actions</i> .....	9
<i>Table 2. Signs per quadrant of Cartesian plane</i> .....	12
<i>Table 3. Commands included in QSM algorithm version 2.21 (source Raunonen et al., 2013)</i> .....	15
<i>Table 4. Settings of QSM used in this research</i> .....	16
<i>Table 5. Grading system for visual sensitivity analysis</i> .....	19
<i>Table 6. Sensitivity analysis results</i> .....	30
<i>Table 7. Sensitivity analysis tests' results showing the sum of grades assigned by the users per PatchDiam2Min values</i> .....	30

## List of Equations

<i>Equation 1</i> .....	16
<i>Equation 2</i> .....	22
<i>Equation 3</i> .....	22
<i>Equation 4</i> .....	24
<i>Equation 5</i> .....	24
<i>Equation 6</i> .....	24

## List of Appendices

<i>Appendix 1. Tree extraction filling form</i> .....	50
<i>Appendix 2. Sensitivity analysis filling form</i> .....	51
<i>Appendix 3. Sensitivity analysis results</i> .....	52
<i>Appendix 4. Filling form for sensitivity analysis tests</i> .....	53
<i>Appendix 5. Output files of AGB from QSM and allometric equations</i> .....	54
<i>Appendix 6. Filling form of TLS stem height estimate per palm tree</i> .....	55
<i>Appendix 7. Field and TLS trunk heights per palm tree</i> .....	55



# Nomenclature

3D	Three dimensional
AGB	Above-ground biomass
CF	Correction factor
cm	Centimetres
DBH	Diameter at breast height
GWDD	Global Wood Density Database
kg	Kilograms
kg/m <sup>3</sup>	Kilograms per cubic meters
km <sup>2</sup>	Square kilometres
LiDAR	Light Detection and Ranging
m	Meters
m <sup>3</sup>	Cubic meters
PSF	Peat swamp forest
PatchDiam2Min	Parameter of QSM: Minimum patch size of the second cover set for tree models
QSM	Quantitative Structure Model
r	Correlation coefficient
r <sup>2</sup>	Coefficient of determination
RMSE	Root Mean Square Error
TLS	Terrestrial laser scanning
WD	Wood density

# 1. Introduction

---

## 1.1 Context and background

Above-ground biomass (AGB) is an important indicator of ecological and management processes in tropical forests. It is defined as the total amount of biological material (usually oven-dried) present above the soil surface in a specified area (Drake et al., 2003; Vazirabad & Karslioglu, 2011). The appropriate estimate of biomass allows to determine the amount of carbon and other existent chemical elements on each of its components. Besides, it represents the potential quantity of released carbon to the atmosphere, or maintained and attached in a certain surface when the forests are managed to reach the goal of greenhouse effect gases mitigation (Brown et al., 1996; Calders et al., 2015; Drake et al., 2003; Schlegel, 2001).

Tropical forests provide various ecosystem services such as carbon storage, wood production, climate regulation and concentration of large amount of biodiversity (Bauwens et al., 2016; Dutrieux, 2016). Furthermore, tropical forests convert more atmospheric carbon into biomass each year than any terrestrial ecosystem, underscoring the importance of accurate tropical forest structure and biomass estimate for the understanding and management of the global carbon cycle (Marvin et al., 2014; Molina et al., 2016). Though, there is an increasing need of accurate and effective methods for AGB estimates and carbon stocks as part of the Kyoto Protocol and REED+ Measurements, Reporting and Verification. (Prasada et al., 2016).

Peatlands are a type of tropical forest ecosystem characterized by the accumulation of decayed organic matter, called peat. (Posa et al., 2011). This peat is formed from plant debris that decomposed slowly under waterlogged anaerobic condition as a result of the high rainfall, topography and bad drainage (Freitas Alvarado et al., 2006; Posa et al., 2011). This particular condition and the geological setting have formed varying thickness layers of peat (Draper et al., 2014). The Peruvian Amazon consists of a characteristic type of tropical peatland vegetation, which is predominantly lowland evergreen forest with the greatest peat depths—and thus carbon stores—, called peat swamp forests (PSF) (Kurnianto et al., 2013; Posa et al., 2011). Nonetheless, there is high uncertainty in the total spatial extent of PSF in the Peruvian Amazon (Draper et al., 2014).

It is important to determine accurate palm structures to use on AGB estimates and develop a further analysis of carbon storage capacity (Freitas Alvarado et al., 2006; Goodman et al., 2013; Marvin et al., 2014). Since palms are one of the main tree species in PSF, and these are considered significant global carbon stores (Draper et al., 2014; Freitas Alvarado et al., 2006; Goodman et al., 2013; Molina et al., 2016; Murdiyarso et al., 2010; Posa et al., 2011). Their degradation and deforestation can severely increase emissions of greenhouse gases and contribute to climate change (Hergoualc'h et al., 2016; Molina et al., 2016; Schlegel, 2001). However, their inaccessibility and the belief that they have lower biodiversity value than upland rainforests lead to relatively less attention from scientists (Prentice & Parish, 1990; Yule, 2008 cited in (Posa et al., 2011)). Additionally, little is known on how the biogeochemical cycle of PSF can be affected through anthropogenic intervention (Hergoualc'h et al., 2016).

This humid and swampy forest is called “aguajal” in Peru. Its name is related to the words “agualotal” and “agualozal”, defined, by the critical etymological Spanish dictionary, as place with stagnant water (Kahn et al., 1993; Rivadeneyra, 1974). There is an estimate of 60 471 km<sup>2</sup> of “aguajales” in the Peruvian Amazon (OSINFOR, 2013 cited in (Freitas Alvarado & Flores, 2015)), being the National Reserve Pacaya Samiria, located in the Loreto region, the area with the highest portion of this PSF, with an approximation of less than 15.000 km<sup>2</sup> of “aguajales” with different densities (CDC, 1993 cited in (Freitas Alvarado & Flores, 2015)).

In the Peruvian Amazon a main candidate for sustainable management is the main palm species *Mauritia flexuosa* or called “aguaje” (Figure 1) (Balslev et al., 2008; Kahn et al., 1993; Manzi & Coomes, 2009). The “aguaje” provides food, fibre, oil, medicinal, material for construction and fishing equipment (Balslev et al., 2008; Goodman et al., 2013; Manzi & Coomes, 2009; Padoch, 1988). Moreover, the commercial extraction of fruit from this palm provides an important source of income for rural communities (Balslev et al., 2008; Gilmore et al., 2013). As well, people who live within or near to Iquitos city consumes the “aguaje” fruit directly or processed into diverse products such as ice cream, popsicles and cold drinks, and is the richest natural source of vitamin A, C and E yet known (Balslev et al., 2008; Freitas Alvarado & Flores, 2015; Gilmore et al., 2013; Manzi & Coomes, 2009). Consequently, the high demand of the *Mauritia flexuosa* fruit often involves to cut down entire palms (Gilmore et al., 2013; Hergoualc'h et al., 2016; Manzi & Coomes, 2009).

Additionally, PSF have a complex structure by the diversity of its vegetation species (Lau Sarmiento, 2014; Palmer et al., 2016; Prasada et al., 2016). Hence, the use of remote sensing techniques is critical to assess a fine-scale spatial variability of tropical forest AGB (Côté et al., 2011; Prasada et al., 2016;

Raumonon, 2015; Raumonon et al., 2015). The emergence of the active remote sensing method called Light Detection and Ranging (LiDAR) in the late 1990s provided new insights to assess forest structure (Calders et al., 2015; Holopainen et al., 2011; Kankare et al., 2013; Prasada et al., 2016; Vazirabad & Karslioglu, 2011). Static terrestrial laser scanning (TLS), also known as ground-based LiDAR (Hopkinson et al., 2004), transmits laser pulses and measure distance by analyzing the returned energy as a function of time (Calders et al., 2015; Holopainen et al., 2011; Kankare et al., 2013).



*Figure 1. Crown of Mauritia flexuosa (Source Kahn et al., 1993)*

TLS is a promising technique for efficient and accurate AGB due to its capacity of direct measurement of vegetation or tree structure and stand characteristics (Holopainen et al., 2011). TLS produces highly detailed point cloud data and it is known as a non-destructive approach (Gonzalez de Tanago et al., 2015; Krooks et al., 2014; Lau Sarmiento et al., 2015; Prasada et al., 2016; Raumonon, 2015; Raumonon et al., 2015). These point cloud data, in combination with quantitative structure modelling (QSM) allows the reconstruction of detailed three dimensional (3D) models of individual trees and canopies (Holopainen et al., 2011; Kaasalainen et al., 2014; Raumonon et al., 2013) to develop quantitative analysis (Kaasalainen et al., 2014). Furthermore, TLS at plot level inventories offers resources to determine basic tree parameters, such as the number and position of trees, diameter at breast height (DBH)<sup>1</sup>, and tree height, in conjunction with automatic data processing (Holopainen et al., 2011).

Additionally, from these 3D QSM models it is possible to measure its volume and convert to AGB using a specific wood density (Gonzalez de Tanago et al., 2015). Therefore, QSM is highly dependent on the scan acquisition parameters and point cloud data quality (Côté et al., 2011; Hopkinson et al.,

---

<sup>1</sup> Diameter of stem measured at a height of 1.3 m (Hackenberg et al., 2014)

2004). Increasing the number of scans has been shown to reduce the errors somewhat (Kaasalainen et al., 2014). However, this point cloud quality is influenced by different factors, for instance the structural complexity of PSF that causes occlusions among the various vegetation components. Thus these occlusions depend on the width of the light beam, the point cloud density, and the use of the first or last return (Côté et al., 2011; Hopkinson et al., 2004).

Other factors which affects TLS data accuracy are: survey locations, number of plots to be surveyed, skill level of people in charge of the survey, type of equipment used, and data analysis methods (Prasada et al., 2016). Moreover, individual extraction of 3D tree produced with TLS data is done manually, which is a challenge and time consuming, and the accuracy and completeness depend on the designed model and the parameters. Further work still needs to be done to refine and to develop an automatic feature identification and data extraction (Côté et al., 2011; Krooks et al., 2014; Prasada et al., 2016). On the other hand, the tree models from point clouds can be produced automatically with algorithms based on reproducing the target structure with voxels or fitting 3D primitives on the tree parts (Côté et al., 2011; Krooks et al., 2014; Raumonon et al., 2015; Vazirabad & Karslioglu, 2011).

## **1.2 Problem definition**

Many of AGB estimates in palm trees have been carried out using AGB regression models for dicotyledonous families (Baker et al., 2004; Chave et al., 2005; Goodman et al., 2013). But, palms are part of the monocotyledonous families. The two groups of plants have very distinct growth patterns and internal composition (Goodman et al., 2013). In palms, the density and stiffness are higher, with a strong stem tissue as a result of its cell structure and chemical composition. Thus, dicotyledonous and conifers have structural integrity during height growth by stem diameter (lateral) growth changes. While palms, a monocotyledons, are characterized by a lacking stem diameter growth change, causing a weak or no relationship between height and diameter (Rich et al., 1986).

Furthermore, young palm trees are overbuilt (thicker stem tissue) with respect to the diameter and older ones are underbuilt (less thick stem tissue) in comparison to dicotyledonous and conifers (Rich, 1987). Besides, palms lack branches in contrast to conifers and dicotyledonous trees (Goodman et al., 2013). Additionally, wood density in *Arecaceae* (palm) family, the single most abundant arborescent plant family in the western Amazon (Goodman et al., 2013; Peñuela Mora, 2014), is generally lower than in dicotyledonous trees (Chave et al., 2009; Zanne et al., 2009 cited in (Goodman et al., 2013)). Therefore, their dissimilarity in height-stem relationship cause the inaccuracy in palm AGB estimates

made from dicotyledonous tree models. Especially with the use of diameter at breast height (DBH), as structure parameter and wood density of dicotyledonous trees (Goodman et al., 2013). The lack of branches in palms can also contribute to an overestimate of AGB since these are considered in the dicotyledonous models (Goodman et al., 2013). Overall, it is clearly a strong need to develop applicable equations to estimate true palm AGB (Goodman et al., 2013).

TLS is also used for AGB estimate. This estimate is, generally, based on indirect relationships with structural parameters, like tree height, which is relevant structural parameter to estimate AGB in palm trees. However, these parameters remain limited in accuracy for quantitative and geometric information of a single tree using TLS (Côté et al., 2011; Krooks et al., 2014). It is researched that tree height estimate accuracy with TLS leads to an underestimate of 1 to 3 m caused by the measure of geometry, which is influenced by occlusions in the highest part of the canopy (Krooks et al., 2014; Palmer et al., 2016).

Even though it is important to estimate AGB from palm trees, specifically for *Mauritia flexuosa* and *Mauritiella armata* species, there are only two studies that estimate its AGB. These studies are based on regression models, and use reference data from destructive sampling to validate the AGB. One research is carried out by Freitas Alvarado et al. (2006), in which the regression model gives an underestimate of AGB for tall palms. The other research is carried out by Goodman et al. (2013), in which allometric equations are proposed for different species of palms. This research validates its AGB estimates with reference data from Freitas Alvarado et al. (2006) (K. Hergoualc'h, personal communication, October 10, 2016). Therefore, AGB estimate in these palm tree species from TLS and tree modelling is pioneering. In addition, due to the absence of reference data, these estimates can be evaluated by comparison with AGB using regression models from previous research.

## 2. Research objective and research questions

---

The main objective of this study is:

To assess AGB of two palm tree species through QSM using terrestrial LIDAR point clouds.

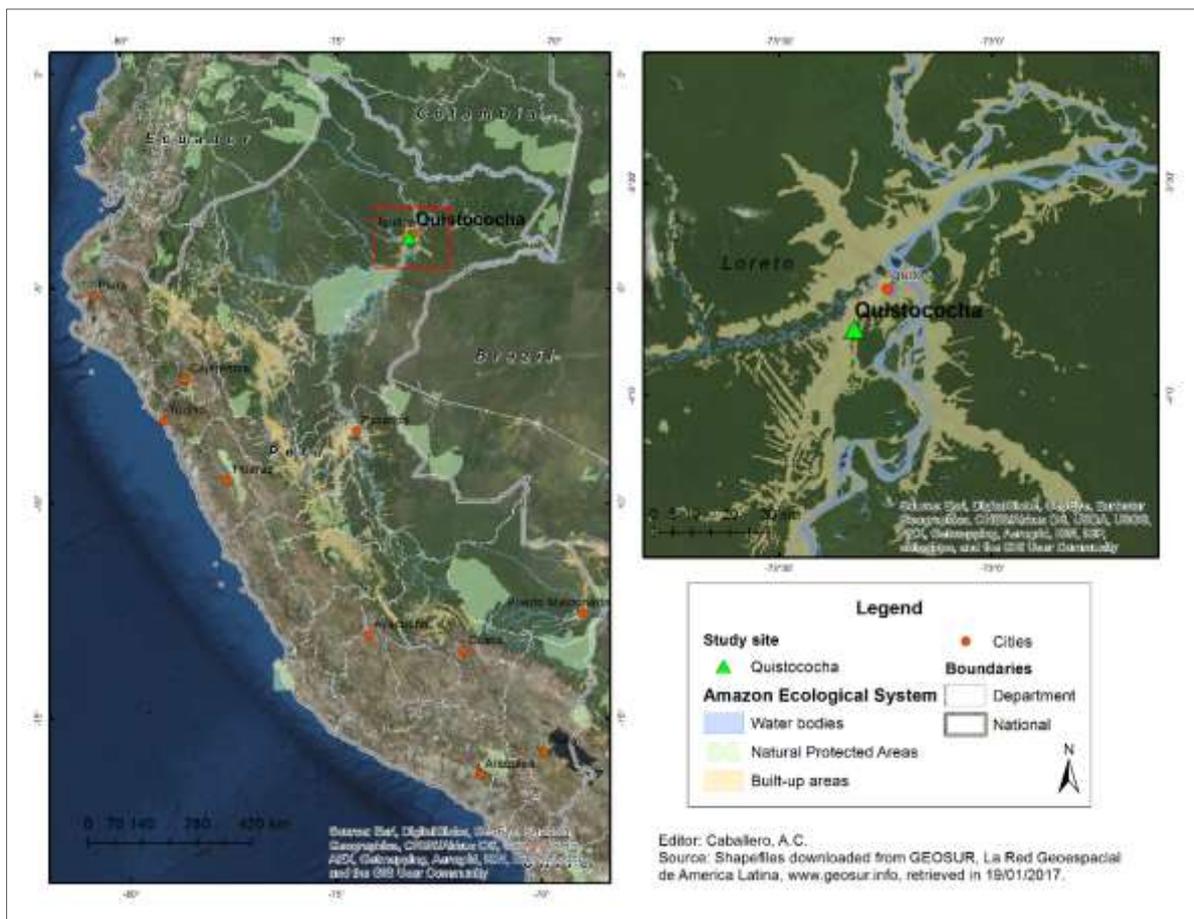
Below are the research questions that will be resolved to answer the main research objective:

1. Which criteria can be used to conduct a visual assessment of palm tree models obtained by QSM?
2. How adequate are the AGB estimates of both palm species using QSM and the available wood density?
3. How comparable are AGB estimates from allometric equations using field inventory or TLS derived stem height?
4. How comparable are AGB estimates from QSM and AGB from allometric equations?

# 3. Materials

## 3.1 Study Area

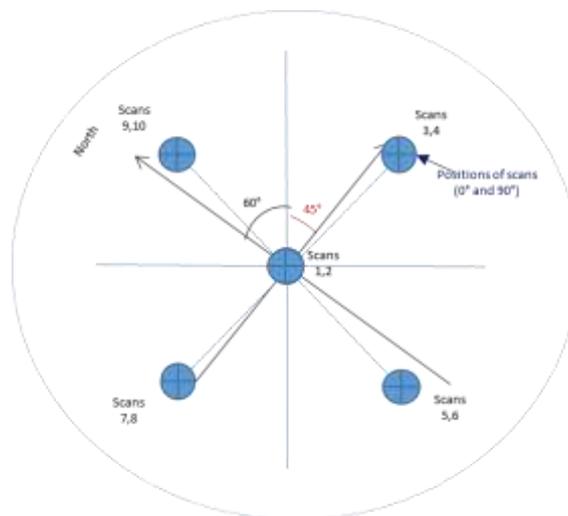
The test site is a pristine peat swamp forest dominated by *Mauritia flexuosa* palms in Quistococha (Figure 2). Quistococha is a National Tourist Park, part of the National Tourist Reserves System of Peru, it is in the south of Iquitos city, known as the biggest metropolis of the Amazon Ecological System in Peru, part of Loreto department. This place is used for research projects, preservation and reforestation (“De Peru.com - Portal de Internet,” 2017).



### 3.2 Data Acquisition

People in charge of fieldwork scanned six plots using one RIEGL VZ-400 V-Line 3D Terrestrial Laser Scan<sup>2</sup> (TLS), within the period from October to December of 2013. Each plot had a radius of 10 m. For this study only four plots were used.

Each plot was scanned from five locations (Figure 3). At each location, two TLS scans were done, first in upright direction ( $0^\circ$ ), then in tilt position ( $90^\circ$ ). These 10 scans form a grid with one centre and four corners. Additionally, each pair of scans in the corners was orientated at a  $45^\circ$  angle, respectively to the transect direction, starting on the upper right location. Furthermore, the scanner was orientated at a  $60^\circ$  angle from the North (A.I. Lau Sarmiento & J. González de Tanago, personal communication, September, 12, 2016).



*Figure 3. Grid of scans per plot*

During scans, it was necessary to put reflectors as markers at the top of sticks. They were located in visible areas, where these were easy to identify in the point clouds from the 10 scans, for example open areas. These markers were used as tie points during pre-processing stage. Data from individual tree were registered in the field inventory such as specie, location, plot, DBH, tree height, trunk length, azimuth, angle and some remarks. From which, tree height and trunk length were taken with a hypsometer.

---

<sup>2</sup> Product of RIEGL Laser Measurement Systems [www.riegl.com]

### 3.3 Software

This study required the use of different software along the methodology process. Table 1 shows the list of the main software applied and the process in which they were used.

*Table 1. Software used: name and actions*

<b>Software</b>	<b>Process</b>
RiScan Pro	Pre-processing and tree extraction, TLS tree height estimation
MATLAB	Quantitative Structure Models
Cloud Compare	Sensitivity Analysis
RStudio	Selection of branch order, volume calculation, AGB estimates from QSMs and allometric equations, results' graphs

As part of the methodology, to obtain different outputs it was necessary to convert text files into 3D data format using python scripts. Moreover, the field data sheets were managed in Microsoft Excel to have a control of the identified palm trees in the point clouds. Likewise, the results of tree extraction, both sensitivity analysis and palm tree heights were documented in Excel tables. Additionally, ArcGIS was used to generate the map of the study site.

# 4. Methodology

The methodology can be divided in three main stages: pre-processing, processing and analysis, as shown in Figure 4. The tree stages are described in detail in the following sections.

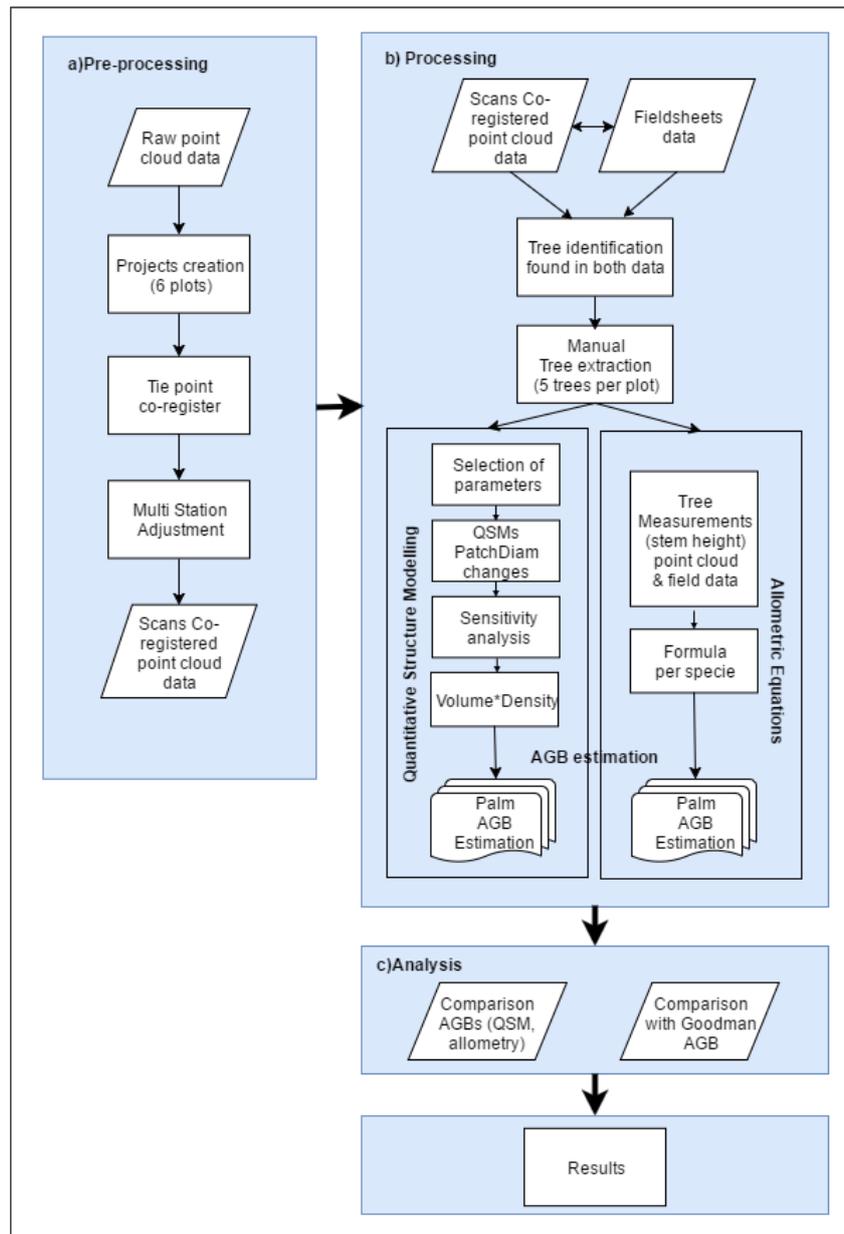
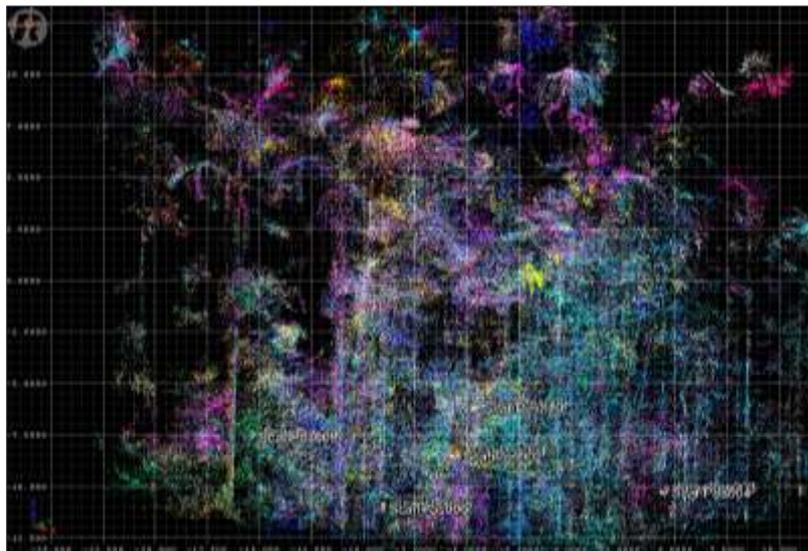


Figure 4. Methodology flow diagram

## 4.1 Pre-processing

The pre-processing stage mainly consisted of co-registration and adjustment of point clouds per plot. The purpose of using 10 scans for each plot was to obtain a higher detail for further analysis. This stage required RiScan Pro<sup>3</sup>, a processing software for RIEGL 3D laser scanners. Therefore, the tie point procedure co-registered the point clouds from the scans, based on the reflective cylinders used as markers. The software linked all the reflectors from the scans, using the centre scan as reference. Then, to improve the point cloud's adjustment, the multi station adjustment tool was performed to reduce any misalignment during co-registration process. This adjustment showed different results, showing the Root Mean Square Error (RMSE) on each result. Thus, I selected the lowest RMSE that made the best fit of the complete plot, as the example showed in Figure 5.



*Figure 5. Co-registered point cloud of Plot 1 after multi station adjustment*

## 4.2 Processing

The processing stage consisted of diverse operations to assess AGB estimates using co-registered point clouds and field inventory data. Therefore, this study focused on the identification of five palm trees of species *Mauritia* and *Mauritiella* per plot, especially on the highest palms registered in the field inventory. This study also considered few small palms; thus, the height varied from 6.75 to 26 m (according to fieldwork data). In total 20 palm trees were selected and cleaned to have individual 3D

---

<sup>3</sup> Software of RIEGL Laser Measurement Systems [www.riegl.com]

objects for the QSM. Then, their volume was obtained and multiplied by wood density to estimate AGB. Furthermore, the 3D palm trees stem heights were used in allometric equations.

#### 4.2.1 Tree extraction

In this step, the chosen palm trees were manually identified on each plot with RiScan Pro software, using the information from fieldwork about distance, azimuth and height. Firstly, due to a little shift at the moment of fieldwork,  $60^\circ$  angle were subtracted to each azimuth angle, because these degrees were the difference in relation to the geographic North, obtaining new angles. Then, depending on the new position that these new angles had in the Cartesian plane, a Quadrant was assigned (e.g. Azimuth  $220 - 60^\circ = 160^\circ$ , quadrant IV). Next, trigonometric functions were applied to these new angles to obtain the X and Y values of each palm tree. These were: the *sin* function to obtain the X and the *cos* function for the Y. After that, depending on the quadrant where the new angle was, the X and Y signs were changed based on Table 2.

Table 2. Signs per quadrant of Cartesian plane

	Quadrant			
	I	II	III	IV
cos (y)	+	+	-	-
sin (x)	+	-	-	+

Finally, with information about the quadrant, the distance from the center scan, the approximate X and Y values and the height (Z value) it was possible to identify 20 palm trees in the 4 point clouds' plots, using the rule and height filter tool. However, palm trees were not exactly in the calculated X, Y location in the point clouds and with a different height. Therefore, I registered the real location, their distance to the center scan and their height in a table to have a complete register form for the 20 palm trees, as it is presented in *Appendix 1*.

Next, the palm trees were cleaned as much as possible to extract a detailed point cloud of individual trees from the ground to the top. Regarding the ground, it was necessary to see where exactly it was, because this does not started in the Z value 0 of the point clouds. Due to the effect of water from PSF, in the scans the trees reflection on the water defined a larger stem than it actually was. Thus, the stem started where the higher number of points was visualized in the height tool of the software. Normally,

the ground started in the Z values from -1.0 to -1.4. Thus, all the points under this Z value were outlying points, which were removed from the polydata<sup>4</sup> of each single palm tree.

In Figure 6 a palm tree found is represented by two pictures, one from the top view and the other from front view. There is difference in the color of height tool due to the variability of point density. Above the lower bar the color is a bit darker and below this bar the color is lighter, which means that the point density is less. This less density confirmed that there is only the reflection of vegetation by the water effect. Therefore, the real base of the palm is represented by the lower bar of height tool, which was important to consider at the moment of measuring the palm tree structure parameters like tree or trunk height.

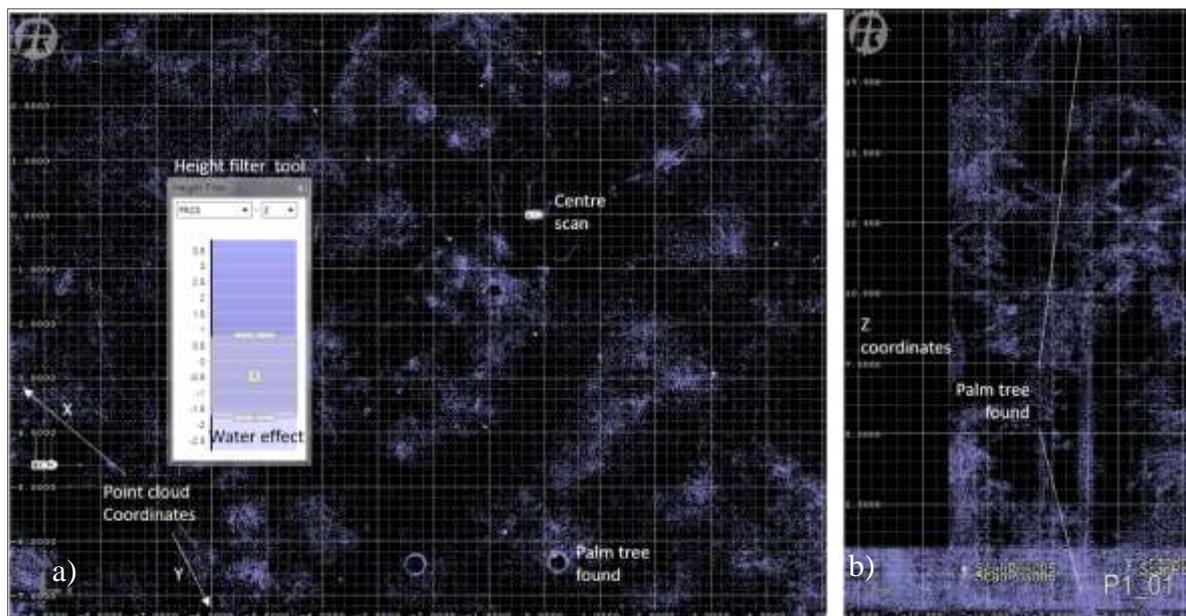


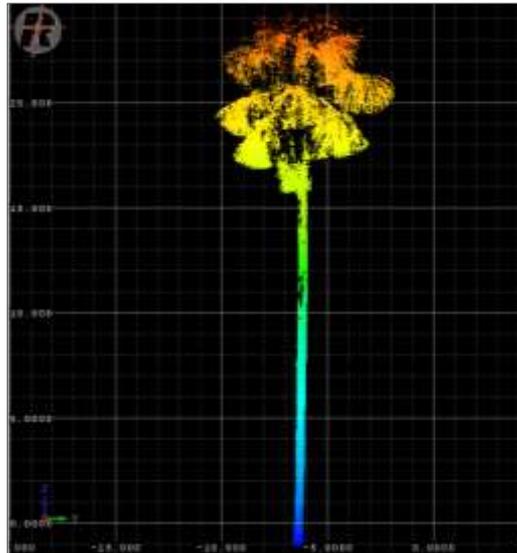
Figure 6. Palm tree found in point cloud using X, Y, Z coordinates, angle and distance to centre scan. a) Top view, b) Front view

Concerning the crown of palms, it was challenging to extract a detail canopy because of the variety of vegetation presented in the point clouds, the fronds<sup>5</sup> of other palms over the selected palm tree. Additionally, the point density decreased rising the canopy, thus above 15 meters the clarity and detail of point clouds were less. Moreover, the shape of palms complicates measurements, especially in the case of *Mauritia flexuosa*, where the fronds hung down covering part of the trunk and causing

<sup>4</sup> Format for point clouds as objects used in RiScan Pro that can be exported to text files in order to save the X, Y and Z coordinates as a matrix of the point clouds.

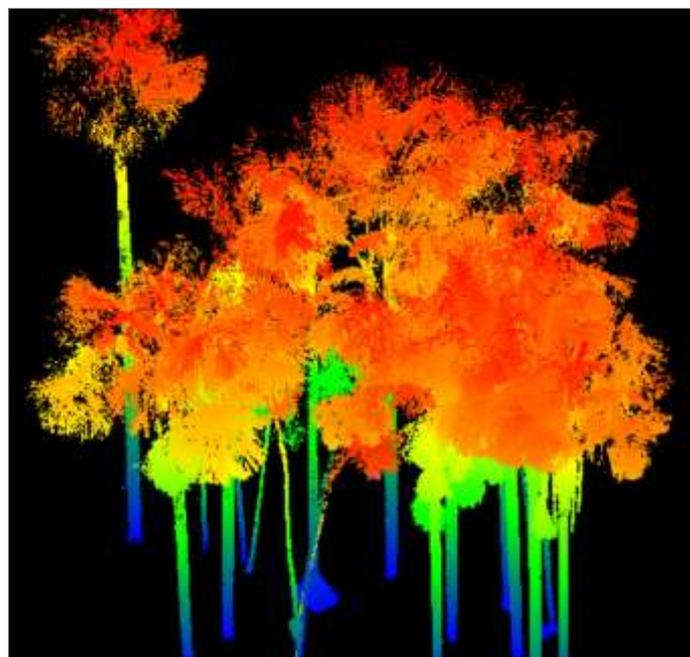
<sup>5</sup> Typical name used for leaves in palm trees.

occlusions during the scan. Figure 7 shows an example of an individual *Mauritia* extracted after the manual cleaning.



*Figure 7. Extracted tree point cloud of Mauritia flexuosa using RiScan Pro*

Next, due to the fact that the X, Y, Z origin of the 20 polydata files processed with RiScan Pro was different on each palm, their origin were moved to a origin 0,0,0 to have better model results and measurements. Figure 8 shows the 20 extracted palm trees together in Cloud Compare after having updated their origin.



*Figure 8. Point cloud of the 20 extracted palm trees*

#### 4.2.2 Quantitative Structure Model (QSM)

Quantitative Structure Models (QSM) are automatic 3D tree structure reconstruction models of the laser scanned trees with TLS (Calders et al., 2015; Raunonen et al., 2015). This method uses the point clouds and it is based on a cover set approach, where points are covered with small sets corresponding to small patches in the tree surface. These patches are the smallest unit used to segment the tree model by rising step-by-step the tree surface until covering trunk and branches (Raunonen et al., 2013).

The tree models are produced with algorithms based on reproducing the target structure based on voxels or fitting geometric primitives approach to the tree (Côté et al., 2011; Kaasalainen et al., 2014; Krooks et al., 2014). They represent the trees as hierarchical groups of these geometric primitives, which provide the volume, diameter of stem and branch segments that are used to estimate the AGB (Raunonen et al., 2015) as a non-destructive method (Kaasalainen et al., 2014).

QSM is different from the voxels approach, because it has been designed to follow the simple morphological rules of tree structure, like branches, as a starting point for the calculation. Then the challenge in the voxel methods is that they require a complete sampling of the tree surface in order to fill the interior voxels. With cylinders the inevitable gaps in the surface sampling and the fact that most branches are sampled only from the bottom side are not so critical (Kaasalainen et al., 2014). Overall, the circular cylinder is the best choice of geometric primitives approach (Raunonen et al., 2015).

In this study, the algorithm used for the QSM is version 2.21 from Raunonen et al. (2013), which builds the palm tree models randomly with cylinders based on the input parameters specified in .

*Table 3. Commands included in QSM algorithm version 2.21 (source Raunonen et al., 2013)*

<b>Parameter</b>	<b>Description</b>
P	Point cloud in text file, the rows give the coordinates of the points.
PatchDiam1	Patch size of the first uniform cover
BallRad1	Ball size used for the first cover set
nmin0	Minimum number of points in BallRad1
PatchDiam2Min	Minimum patch size of the second cover set
PatchDiam2Max	Maximum patch size in the base of the stem of the second cover
BallRad2	Maximum ball size used for the second cover set
Nmin	Minimum number of points in BallRad2

Lcyl	Cylinder length/radius ratio
OnlyTree	Logical value, true if points belong to the tree, in which case the base of the stem is defined by the lowest part of the point cloud
string	Name to save the model

The algorithm followed the Equation 1. In which the parameters *PatchDiam1*, *BallRad1*, *PatchDiam2Min*, *PatchDiam2Max*, and *BallRad2* were expressed in units of the point cloud (metres):

$$3D \text{ tree model} = \text{qsm\_tree}(P, \text{PatchDiam1}, \text{BallRad1}, \text{nmin1}, \text{PatchDiam2Min}, \text{PatchDiam2Max}, \text{BallRad2}, \text{nmin2}, \text{l cyl}, \text{OnlyTree}, \text{string}) \quad \text{Equation 1}$$

There were some trials changing the parameters in order to visualize the changes in the results of 3D palm tree models. However, because of the difference in height, the diversity of detail on each palm tree point cloud and the lack of time of this study, the only parameter changed to obtain the QSMs for this study was the *PatchDiam2min*. lists the final values selected for each parameter of the algorithm after doing these trials, since these values provided acceptable models of the palm trees even with different height and specie.

*Table 4. Settings of QSM used in this research*

Parameter	Value			
P	Text file of point cloud			
PatchDiam1	0.15			
BallRad1	0.17			
nmin0	5			
<b>PatchDiam2Min</b>	<b>0.02</b>	<b>0.04</b>	<b>0.05</b>	<b>0.06</b>
PatchDiam2Max	0.1			
BallRad2	0.14			
Nmin	3			
l cyl	3			
OnlyTree	1			
string	name of the resulting file			

This version of the QSM fitted two cover sets, the first cover used larger sizes than the second cover set. The first cover had a small effect on the result, its purposes were the removal of outlier points that did not belong to the palm tree, for example, points under the ground or along the structure. It also makes the initial segmentation of the trunk and branches structure. The *PatchDiam* was the minimum distance between close centres of cover sets. Thus, the value was 0.15. It had to be a bit lower than *BallRad1*, which was 0.17, with *nmin1* of 5 points.

On the other hand, the second cover had more effect on the results and it was possible to define minimum and maximum values. Thus *PatchDiam2Min* was the one which changed from 0.02 to 0.06 while the *PatchDiam2Max* was 0.1 and the *BallRad2* had to be at least the *PatchDiam2Max* plus 0.01. But if the point density was lower the difference could be bigger, therefore the *BallRad2* was 0.14 due to the variety of detail in the point clouds per palm tree; and the *nmin2* of 3 points.

The parameter which had the major influence in the results of the QSMs was the minimum patch size of the second cover set (*PatchDiam2Min*), expressed in units of the point clouds (metres). Hence, this parameter was changed with the 4 variable to run 10 random models that allowed to do a sensitivity analysis. The different values were 0.02, 0.04, 0.05 and 0.06 in order to avoid a number higher the *PatchDiam2Max*, which was 0.1, due to this was the maximum value for the second cover set.

For the last two parameters, *lcyl*, which was the relative length of cylinders defined as 3, because the shorter the length was, the better the local diameter of the trunk and branches was. Nevertheless, it also could produce noise in the diameter due to some shifts to cover the structure. Regarding *OnlyTree*, the value was 1 that means True since the base of the trunk was defined, then the segmentation started from this base. Finally, *P* was the file of each individual palm tree point cloud with the 0,0,0 origin with the info about X, Y, Z coordinates, and the *string* was the given name for the results.

The QSM created 3 output files with data about the 3D tree model (Figure 9). These files were: *cyl\_data\_filename.txt*, *branch\_data\_filename.txt* and *tree\_data\_filename.txt*. The full description about the components of these files are found in Appendix II from the research of Lau Sarmiento, (2014). This study only used the *cyl\_data* file because it contained the location of the cylinders.

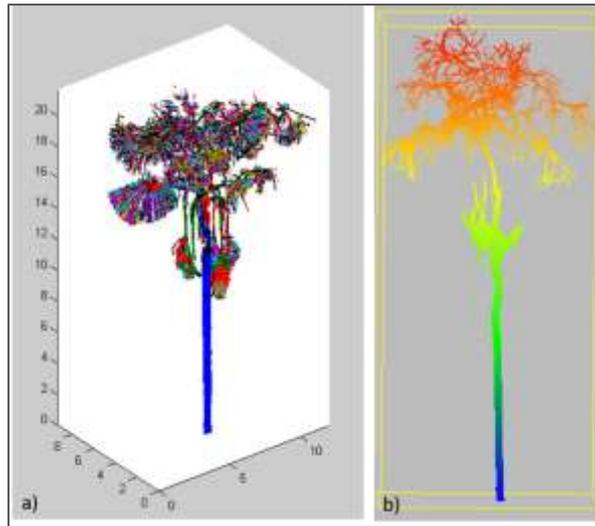


Figure 9. 3D QSM palm tree (*Mauritia*). a) Figure result from MATLAB, b) 3D figure visualized in Cloud Compare

### 4.2.3 Sensitivity Analysis

The algorithm from Raunonen et al. (2013) builds palm tree models based on the random assignation of the first patch set. Even with the same parameters, each model is slightly different, thus it is recommended to fit 5 to 10 models per palm tree (Raunonen et al., 2013). Due to this reason a loop of 10 models per each *PatchDiam* (0.02, 0.04, 0.5 and 0.06) for each of the 5 trees was generated in every plot. The first round produced a total of 200 models using the *PatchDiam2Min* value of 0.02 m, including all the information about the cylinders. Simultaneously, the next 200 models with a *PatchDiam2Min* value of 0.04 were performed and so on until 800 QSMs were obtained in total. Afterwards, I analysed visually each one of these 800 3D palm tree models.

According to the literature reviewed, and specially supported on the AGB estimate proposed by Goodman, et al. (2013) for *Mauritia* and *Mauritiella* species, this study followed a visual analysis focused only in the model of the stem for two reasons: 1) because the QSM classified the fronds as branches instead of classified them as leaves, then if these fronds are considered for the AGB there is an overestimate since palms lack branches and 2) to obtain results that could be more comparable with the results from allometric equations.

Visual analysis was performed on each of the 10 QSM palm tree models by each of the four groups of *PatchDiam* (using 0.02, 0.04, 0.5 and 0.06). This analysis established a grading system from 0 to 3, where 0 represented the worst fit model and 3 represented the best fit model as Table 5 describes. This grading system focused on the straightness of the cylinders and the coverage of the trunk diameter,

which helped to see which value of the minimum patch size for the second cover defined the best 3D model for each of the 20 palm trees.

Table 5. Grading system for visual sensitivity analysis

Grade	Description
0	Trunk model form is slightly similar from the point cloud. Few cylinders are covering the diameter of the trunk. Many of the cylinders in the trunk are shifted. There are isolated cylinders in the area of the trunk.
1	The form of the trunk model is moderately similar to the point cloud. A small amount of cylinders are straight as the trunk form instead of being shifted. The diameter of the cylinders is moderately similar to the diameter of the trunk.
2	The form of the trunk model is very similar to the point cloud. Some cylinders are straight as the trunk form instead of being shifted. The diameter of the cylinders is very similar to the diameter of the trunk.
3	The form of the trunk model is extremely similar to the point cloud. Most of the cylinders are straight as the trunk form instead of being shifted. The diameter of the cylinders is extremely similar to the diameter of the trunk.

Figure 10 shows an example of a visual sensitivity analysis for the case *Mauritia flexouosa*, and Figure 11 displays an example of *Mauritiella armata*. Both figures present the fit of QSM in the point cloud and the accuracy of models goes from left to right, being the first model the most accurate. Moreover, the red and yellow circles, respectively, represent the main aspects considered to give the final grade.

For instance, in *Mauritia* the grade 3 palm had a wider stem almost covering the point cloud and cylinders were straighter than grade 2 palm. Grade 1 palm had a narrower stem than grade 2 and shifted cylinders, and grade 0 palm had truncated trunk and narrower stem than grade 1 palm. Furthermore, in the case of *Mauritiella*, the differences are a bit less visible on the images, but grade 3 palm had also wider and straighter stem than grade 2 palm. Cylinders of grade 2 palm were a bit shifted; grade 1 palm are more shifted and had a zig-zag structure; and grade 0 palm had a narrower stem and shifted cylinders.

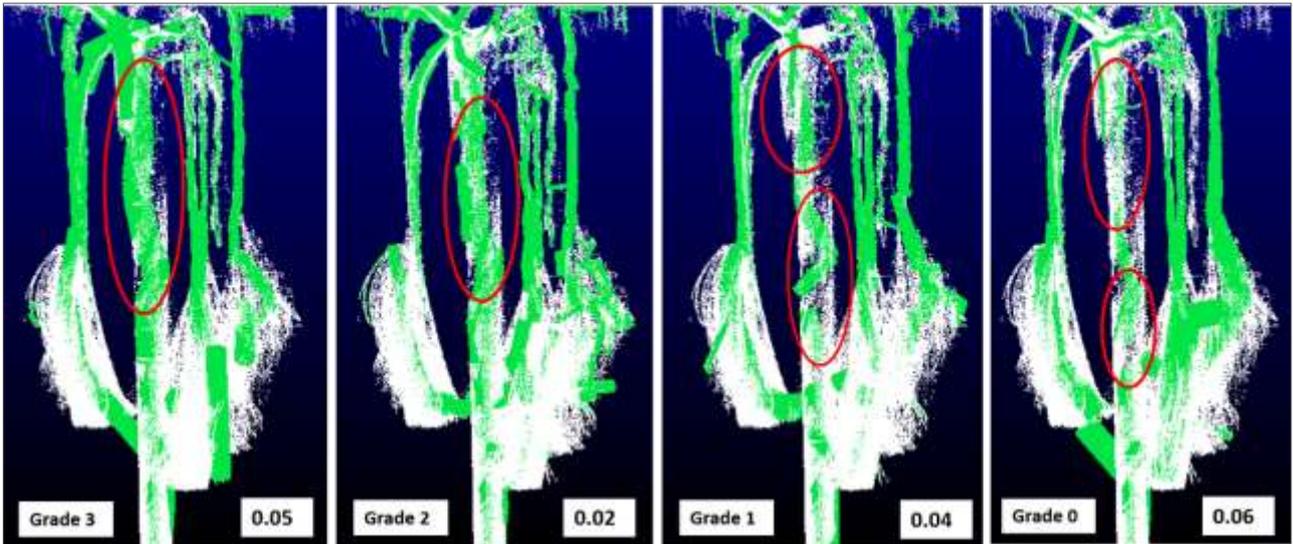


Figure 10. Sensitivity analysis of *Mauritia flexuosa*. Left box presents the grade and right box shows the *PatchDiam2Min* value. Red circles mark the main aspects considered to define the grade

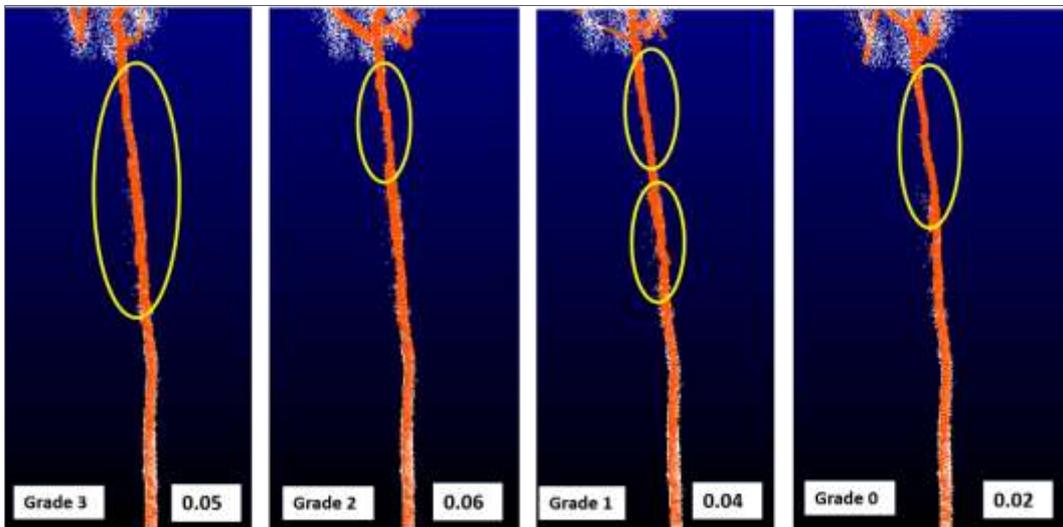


Figure 11. Sensitivity analysis of *Mauritiella armata*. Left box presents the grade and right box shows the *PatchDiam2Min* value. Yellow circles mark the main aspects considered to define the grade

Then, the grade of each palm tree was registered in a table filling form (*Appendix 2*). Once the 40 models of the first palm tree were checked, the results were summarized and the highest total represented the most appropriate value of *PatchDiam2Min* to use for the best fit QSM of that palm tree and so on until the last palm. Finally, expecting that the results were not the same in all the trees and to identify possible differences per species, the best value of parameter *PatchDiam2Min* per palm tree was registered in an Excel form showed in *Appendix 3*.

#### 4.2.4 AGB from QSM

The QSM built a level of branches starting with the stem until it reached the last branch at the top of the tree. But, palm trees lack of branches, therefore only the stem was taken into account to estimate the AGB. Normally, the level one of branches models the entire stem, hence it was convenient to confirm if, indeed, just the first level was necessary; otherwise, there could be an underestimate of AGB due to the lack of cylinders considered.

Then, the cyl\_data file from QSMs was used to estimate the radius and length of all the cylinders to calculate the volume that is used for AGB estimates. Moreover, the column with information about the branch order was considered on the volume calculation, in order to have only the volume of stem. Before knowing the branch order of the stem, it was necessary to visualize the classification of branches of the entire 3D model. I made this visualization manually in Cloud Compare using the option Display Ranges, which draws the order of branches with different colours as Figure 12 shows. To find the most adequate order of branches for the stem, a selected order was displayed with colours while the other orders were coloured in grey as Figure 13. Displays of palms' QSMs branch order that covers the trunk. a) *Mauritia*, b) *Mauritiella* Figure 13 shows.

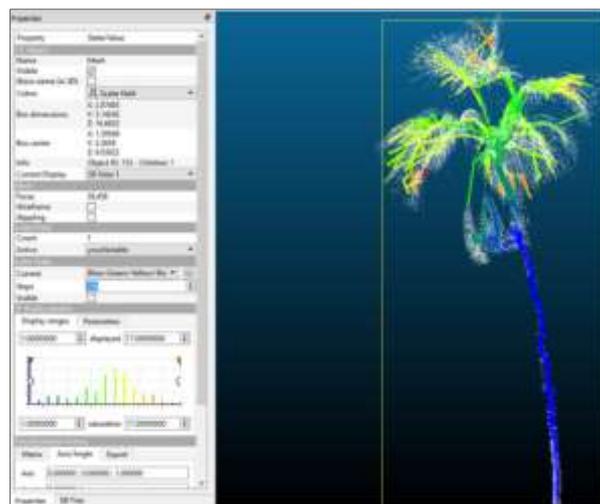


Figure 12. Display of *Mauritiella* QSM in Cloud Compare showing all the branch orders

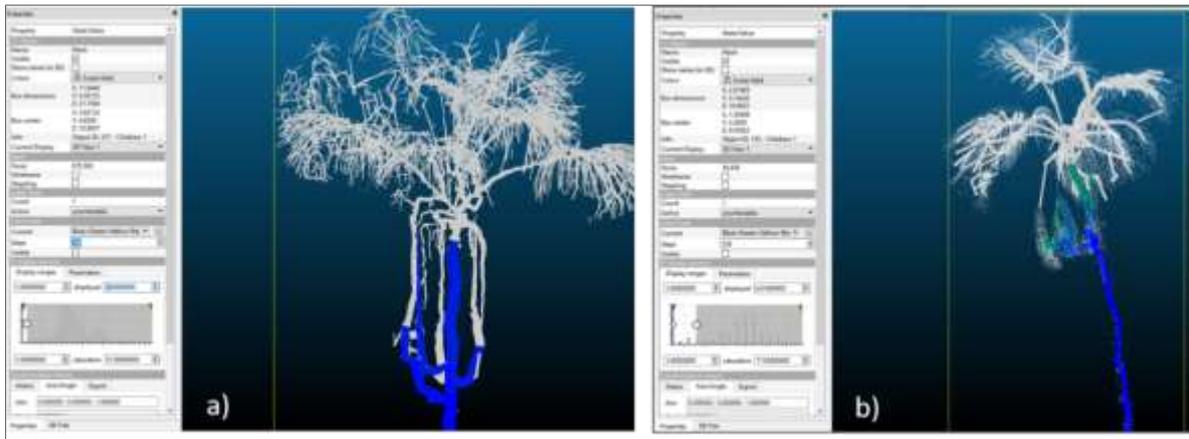


Figure 13. Displays of palms' QSMs branch order that covers the trunk. a) *Mauritia*, b) *Mauritiella*

Only 50 palm tree models of both species and with different heights were checked to identify a trend in the branch order that defined the trunk. Hence, the decision was to use until order 3. Though, it is important to mention that in all the cases were variances due to the defined order covered the whole stem, part of it or few branches more than the stem. For few models the order 2 completely covered the stem, for some models was the order 3 and for others were until 4. Thus, with the purpose of defining which one was the best choice, the volume of these cylinders classified from order 1 to 3 was summarized separately and the results were the same, until order 4 there was a minimal change. However, it was considered not feasible to use the order 4 with the intention to avoid a higher overestimate.

Next, the volume of each cylinder of the whole palm models was calculated with the Smalian's formula (Ministry of Forest, 2011) until the defined branch order which covered the entire trunk. This formula was used on the basis of the modelling process did not create cylinders with the same diameter in bottom and top circles. presents this formula:

$$V = \frac{A_1 + A_2}{2} * L \quad \text{Equation 2}$$

Where V is the volume of each cylinder in m<sup>3</sup>, A<sub>1</sub> is the area of the small end of the cylinder in m<sup>2</sup>, A<sub>2</sub> is the area of the large end of the cylinder in m<sup>2</sup> and L is the length of the cylinder in m (Ministry of Forest, 2011). Furthermore, the mass formula represented in the was used to calculate the AGB (in kg units):

$$\text{mass} = \text{volume} * \text{density} \quad \text{Equation 3}$$

Where the volume (in m<sup>3</sup> units) is the mean volume of the 10 models that represented the best fit value of *PatchDiam2Min* of each of the 20 palm trees. And the density is the WD (in kg/m<sup>3</sup> units), which value (to lead an accurate AGB outcome), has to be specific per palm species due to the palm WD varies 10-fold between species and even within individuals (Rich, 1987 cited in (Goodman et al., 2013)). However, there are not available WDs for *Mauritia* and *Mauritiella* species in the Global Wood Density Database (GWDD) (Zanne et al., 2009). Moreover, there is an absence of reference data from which is possible to obtain WD as in the research of Freitas Alvarado et al. (2006) and Goodman et al. (2013).

Therefore, two WDs were used in this research, obtaining two AGB estimates (*Appendix 5*). The first WD was 640 kg/m<sup>3</sup> taken from a research by the government of Peru regarding the estimate of carbon content in the Peruvian forests, (Ambiente, 2014). And the second WD was 426 kg/m<sup>3</sup>, which was the mean of all trees from the Areaceae (palm) family in the South America tropical region from the GWDD (Zanne et al., 2009). However, it is important to mention that it was known in advance that this second WD could cause overestimates after a discussion with an expert. She strongly advised to not use the mean of WDs due to a huge variety of WD within palm family (R. Goodman, personal communication, December, 12, 2016).

#### **4.2.5 AGB from allometric equations**

The use of allometric regression models is a crucial step in estimating forest biomass (Chave et al., 2005), being the most widely non-destructive used method (Vashum & Jayakumar, 2012). The allometric equations are developed by establishing a relationship between the different physical tree parameters such as DBH, tree height, stem height, crown diameter, etc. These equations are developed for single species or for a mixture of species in order to provide the biomass for specific sites and make comparisons in a regional or larger scale (Vashum & Jayakumar, 2012).

Allometric equations are considered to be a non-destructive method or an indirect method since these only use the best indicator parameter obtained from the forest inventories to estimate the biomass (Vashum & Jayakumar, 2012). Nevertheless, the predictive power of these models depends on how well they are validated using tree biomass data obtained directly from destructive harvest experiments (Chave et al., 2005).

There are few accepted and applicable biomass equations for palms, some are created for single species and often do not cover a wide range of sizes (Goodman et al., 2013). Most of the equations are built under the simple form:  $AGB = a + bx$ , but plant allometric relationships do not usually follow this

simple linear relationship. Stem height is the most common used predictor variable (x) for palm AGB, but also tree height, age and DBH have been used (Frangi & Lugo, 1985; Goodman et al., 2013). In this research, the allometric equations to estimate AGB in kg for both palm species were the ones developed by Goodman et al. (2013). The Equation 4 represents the allometric equation for *Mauritia flexuosa*:

$$\ln(AGB) = 2.4647 + 1.3777 * \ln(Hstem) \quad \text{Equation 4}$$

Where *Hstem* is the stem height, which is the height measured from the ground to the point where the first (lowest) leaf (frond) parted from the stem (Goodman et al., 2013). This equation is a logarithmic regression, therefore it was necessary to transform the logarithm of AGB outcome in order to express estimated values in arithmetic units (Baskerville, 1972). Thus, to solve the logarithm of AGB, it was necessary to apply the correction factor (CF)  $\exp(RSE^2/2)$ , where the RSE is 0.2727 (Goodman et al., 2013). To obtain the final AGB outcome for *Mauritia*, Equation 5 expresses in detail the above allometric equation with the logarithm transformation:

$$\exp(2.4647 + 1.377 * \ln Hstem) * \exp (0.2727^2 / 2) \quad \text{Equation 5}$$

The Equation 6 is the allometric equation for the *Mauritiella armata*, which did not need any logarithm transformation:

$$AGB = 2.8662 * Hstem \quad \text{Equation 6}$$

Subsequently, AGB was calculated applying these allometric equations on each of the 20 palm trees. The fields of the output files are explained in *Appendix 5*. Furthermore, it was necessary to verify if the heights between the one taken in field and the one from TLS point clouds were the same; likewise, AGB had to be estimated using both heights.

### 4.3 Analysis

The last stage of methodology was analysis, in which users tested the sensitivity analysis considering that this examination can very subjective. It was also important to assess information from the field inventory measurements and data from the TLS to see variances between both.

#### 4.3.1 Sensitivity Analysis tests

To evaluate the robustness of the proposed grading system as part of the visual assessment in 3D palm tree models, 7 students of the Master Geo-Information Science (MGI) executed the same sensitivity analysis for four models of one palm per plot, two *Mauritias* and two *Mauritiellas*. The palm tree models were selected randomly, having a total of 64 3D models. The students had knowledge in remote sensing and were familiar with point clouds, tree modelling and biomass estimation; they also visualized and evaluated the models registering their results in a filling form showed in *Appendix 4*.

Afterwards, on each test the grades of the 3D models per *PatchDiam* (in total 4) were summarized on the first palm tree, then the next palm and so on until the fourth palm. Then, these 4 sums per palm tree from each test were collected in a table to have the sums of all the tests together. Lastly, these final sums were compared with the results obtained from the sensitivity analysis explained in the subsection 3.2.3. Even when this visual assessment could be very subjective, it was part of the analysis to support the feasibility of the grading system proposed in this research. Moreover, to find if this scale was easy to understand for the users with the aim to evaluate visually the 3D palm tree models, and finally to compare their outcomes with the results of this research.

#### 4.3.2 Comparison of field and TLS data

To assess the AGB from allometric equations this study based on the correlation of results using field inventory and TLS point clouds measurements. This research considered only the trunk height measurements registered in the field inventory, because is the same tree element used in allometric equations.

While for measuring the trunk height from point clouds, the process was done manually with RiScan Pro software using the *cyl\_data* file of each of the 20 extracted palm trees. First, a point was created at the top of the trunk, considering the definition of stem height in (Goodman et al., 2013). This stem height is the highest point of stem where the first (lowest) leaf parts from the stem. Once the point is drawn, the software showed the Z value as Figure 14 displays. Then, another point was created at the bottom of the palm to also obtain the Z value as Figure 15 shows. Next, I registered these two values in a table to calculate the TLS height just subtracting the Z bottom value from the Z top value (*Appendix 6*).

Having the heights of the 20 palm trees from the two sources (field and TLS) (

Appendix 7), the AGB in  $\text{kg}/\text{m}^3$  was calculated using the allometric equations per species. Finally, with these data was possible to make comparisons between these two AGB estimates, with the results from Goodman, et al. (2013), and between the AGB from allometric equations and AGB from QSM.

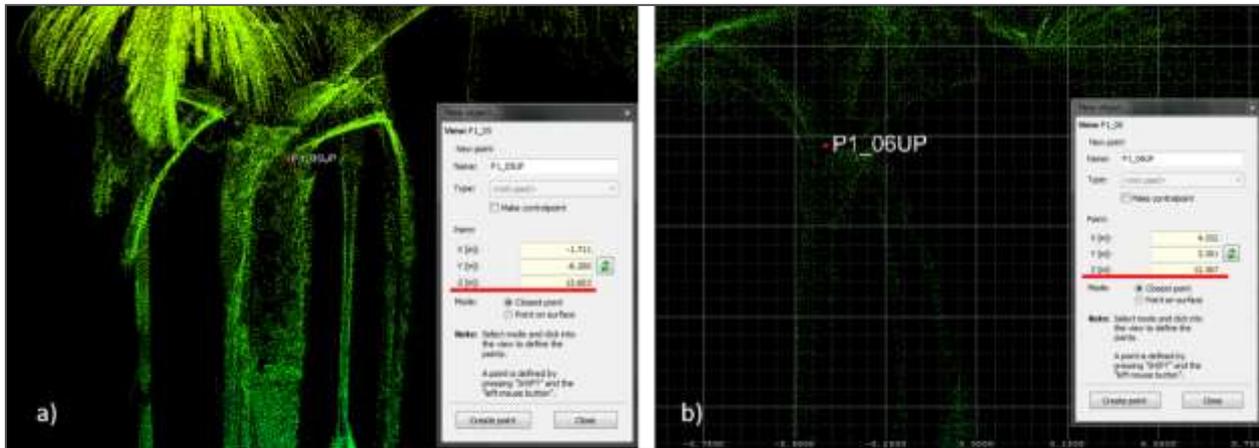


Figure 14. Point showing the Z value at the top of the stem in TLS point cloud. a) *Mauritia*, b) *Mauritiella*

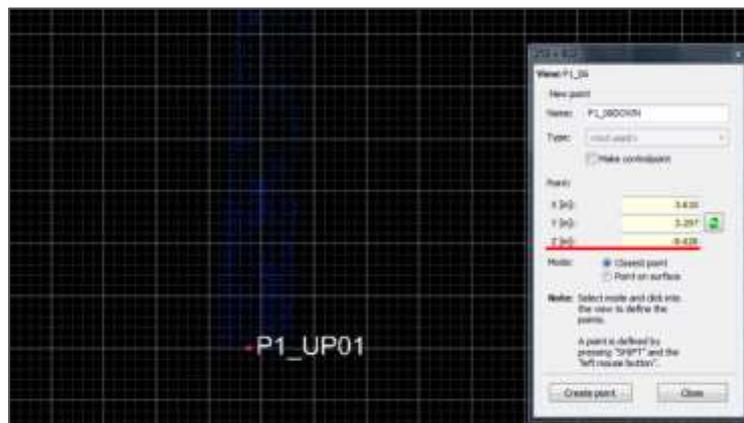


Figure 15. Point showing the ground point and Z value in TLS point cloud

# 5. Results

---

## 5.1 Tree extraction

The result of the tree extraction was an amount of 20 point clouds of both species of palm trees that varied in level of detail. 12 palms were *Mauritia flexuosa*, example of this species are showed in Figure 16a and Figure 16b. For *Mauritiella armata* species were 8 palms, and two examples are showed in Figure 16c and Figure 16d.

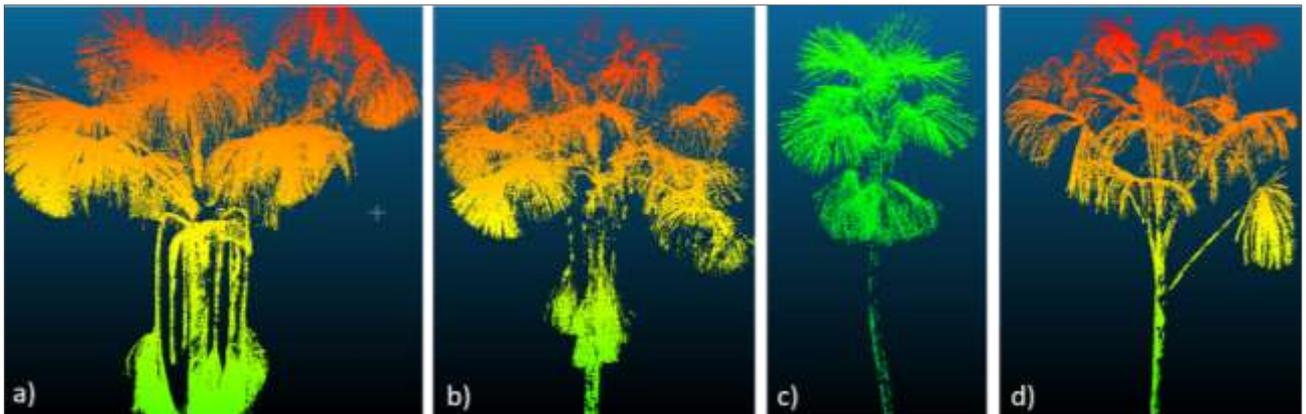
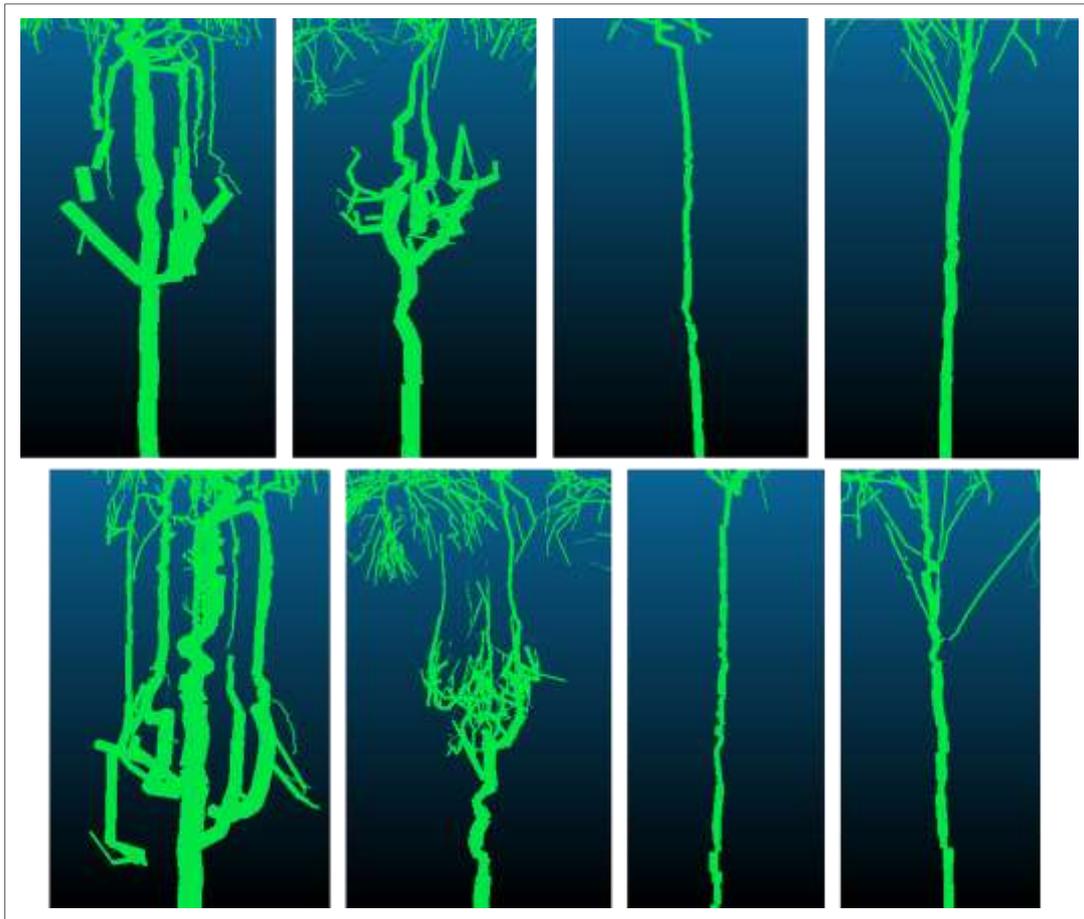


Figure 16. Examples of extracted palm trees per species. a), b) *Mauritia* and c), d) *Mauritiella*

To obtain accurate QSMs for a precise AGB estimate, the objects extracted from the point clouds needed to have a high level of detail. But, this high detail is mainly influenced by the precision of the scans, the palm species, the abundance of surrounding vegetation (occlusion) and the palm height. Therefore, not all the 20 palms had the same level of detail, especially the palm species *Mauritia*. In these cases particularly, leaves hang down and cause occlusion in the area where the first leaves parted from the stem. Moreover, at higher heights (over 15 meters) the number of points is fewer, because of the less range of laser beam over this height. Furthermore, palms within dense vegetation areas have less level of detail. In contrast, if there are gaps of vegetation or shorter trees, the amount of points is higher.

## 5.2 Quantitative Structure Model (QSM)

The second processing step was performing the QSM, which needed to estimate the volume and assess AGB. Therefore, the values for the parameters used in the algorithm of Raunonen et al. (2013) were defined considering the variety of characteristics such as palm species, height and quality of point clouds. These were the same for the 20 palms, and *PatchDiam2Min* was the only parameter changed 4 times, in order to create a high number of models per palm tree. For each of the 4 *PatchDiam*, 10 models were made. Thus, these repetitions were 10x4x20 having a total of 800 palm tree 3D models. Figure 17 presents some examples of 3D palm tree models results for both species focusing on the stem part. The first row in the figure are example of good stem models while the second row are examples of less quality stem models.



*Figure 17. Examples of QSMs. Upper images represent good stem model and below images show less quality stem model*

Starting from the base of palm trees, in general, the QSM models the stem better than the canopy due to the straight structure of the trunk and the absence of branches along the stem as in coniferous trees. Going up to the top of the stem, there are higher differences and the accuracy of the structure becomes

less because of the lack of points up to 15 meters. Additionally, in the case of *Mauritia* species, due to the disposition of its first leaves part of the trunk is covered that causes a negative effect on the 3D model. Hence, the algorithm, in some cases, models these leaves as a continuation of the trunk, building a shifted trunk structure or a trunked stem. An example of *Mauritia* with a trunked stem is visible in the second image (from left to right) in the second row of Figure 17.

On the other hand, in some cases of *Mauritiella* species, the most common structure is like a zig-zag modelling because the detail of points is less due to the narrow stem of this species. Therefore, at the moment of scanning the laser beam cannot reach the entire surface as an effect of its resolution and range distance. Furthermore, the surrounding vegetation occluded the scans causing a less point density. Two examples of *Mauritiella* with zig-zag stem structure are showed in the third and fourth image (from left to right) in the second row of Figure 17. Regarding the canopy, the QSM models the fronds as branches due to their extended shape, which is not completely correct. However, for this study the canopy was not evaluated since it was not considered for AGB estimates.

### 5.3 Sensitivity analysis

For the visual evaluation on *Mauritia* and *Mauritiella* palm species models, the part of the palm tree to evaluate was determinant. According to Goodman et al. (2013), in allometric equations the trunk height is used to estimate AGB of these two palm species. Therefore, the stem was also considered in the visual assessment of QSM palm tree. Additionally, the visual assessment was based on a grading system of 4 grades, which focused on the cylinder reconstruction of the trunk. The criteria of this grading system assessed the cylinder delineation over the point cloud, and the straightness of the cylinders to have an accurate volume estimate to use on AGB formula.

Considering these evaluation criteria, the visual assessment was conducted on the 800 palm tree 3D models. Table 6 presents the results, in which the *PatchDiam2Min* 0.06 m modelled the most appropriate 3D palm tree stem structure for *Mauritia* and *Mauritiella*. These results showed that 70% of the 20 total palm trees were modelled accurately when using *PatchDiam2Min* 0.06 m, while only 20% and 10% of the palm trees were accurate using *PatchDiam2Min* 0.05 and 0.02 respectively.

Overall, it is showed that the higher the value of *PatchDiam2Min*, the better the palm tree model is. Consequently, apart from the importance of the most appropriate selected values for the parameters,

the accuracy of models depends on the detail of point clouds. Thus, if point density decreases, especially at higher height, the 3D model is affected.

Table 6. Sensitivity analysis results

Species	PatchDiam2min			Total
	0.02	0.05	0.06	
<i>Mauritia flexuosa</i>	1	3	8	12
<i>Mauritiella armata</i>	1	1	6	8
<b>Total</b>	<b>2</b>	<b>4</b>	<b>14</b>	<b>20</b>
<b>%</b>	<b>10</b>	<b>20</b>	<b>70</b>	<b>100</b>

Regarding the results of sensitivity analysis tests with MGI students, Table 7 shows that the summary of the grades from the tests are very similar to the ones obtained in this research, with little variations in the results for the cases of *Mauritia flexuosa*. The variations in the results are explained, principally, by the high effect on the 3D model caused by the complex form of *Mauritia*, because the fronds cover the top of the trunk as it is explained above in 5.2 and 5.3 sections.

Table 7. Sensitivity analysis tests' results showing the sum of grades assigned by the users per PatchDiam2Min values

TreeID		P1_05		
Species		<i>Mauritia</i>	<i>flexuosa</i>	
PatchDiam2Min	0.02	0.04	0.05	0.06
<b>Tests</b>	31	41	34	62
<b>Research</b>	9	15	21	15

TreeID		P2_04		
Species		<i>Mauritiella</i>	<i>armata</i>	
PatchDiam2Min	0.02	0.04	0.05	0.06
<b>Tests</b>	11	41	50	68
<b>Research</b>	0	13	19	28

TreeID		P3_03		
Species		<i>Mauritia</i>	<i>flexuosa</i>	
PatchDiam2Min	0.02	0.04	0.05	0.06
<b>Tests</b>	4	38	65	65
<b>Research</b>	5	16	19	20

TreeID		P4_09		
Species		<i>Mauritiella</i>	<i>armata</i>	
PatchDiam2Min	0.02	0.04	0.05	0.06
<b>Tests</b>	21	41	51	56
<b>Research</b>	1	12	20	27

Thus, the 3D model fit to the point cloud varies hugely in *Mauritia* being the accuracy of models more critical to evaluate in *Mauritia* than *Mauritiella*, as students mentioned. In comparison, the models of *Mauritiella armata*, are easier to evaluate because the trunk is not covered by the fronds. Hence, the results are the same, confirming that the best fit QSM is performed with *PatchDiam2Min* 0.06 m.

#### 5.4 Comparison of AGB estimates from QSM using different wood densities

To obtain AGB the mean volume (in m<sup>3</sup>) of the 10 best fit QSM per each of the 20 palm trees was multiplied by WD (kg/m<sup>3</sup>). Nevertheless, due to the absence of specific WD for *Mauritia* and *Mauritiella* two WDs were used in this research, and a comparison was made to see the differences between AGB estimations. The first WD from Peru government was 640 kg/m<sup>3</sup>, and the second WD from GWDD was 426 kg/m<sup>3</sup>. The AGB estimate for both palm species with the first WD was high and the AGB with the second WD was low as it is showed in Figure 18a and Figure 19a.

Comparing AGB of *Mauritia* using two WDs, there is a considerable difference as Figure 18b shows. In fact, the mean of the difference in AGB for the 12 *Mauritias* is 316 kg. On the contrary, the difference of AGB in *Mauritiella* is less as Figure 19b shows. For which the mean of the differences between both AGB estimates from the 8 palms is 32 kg. The difference of AGB using both WDs in these palm species demonstrates that, indeed, WD has an important effect on AGB outcome. Therefore, considering a difference of around 200 kg/m<sup>3</sup> between both WDs, it was expected that the high WD gave a higher estimate. Furthermore, not only WD has an effect on AGB, the volume from the QSM also affects, which at the same depends on the form of the species. Thus, the variety on AGB between these two palm species is explained because *Mauritia* has a wider stem than *Mauritiella*, which causes a higher AGB estimate.

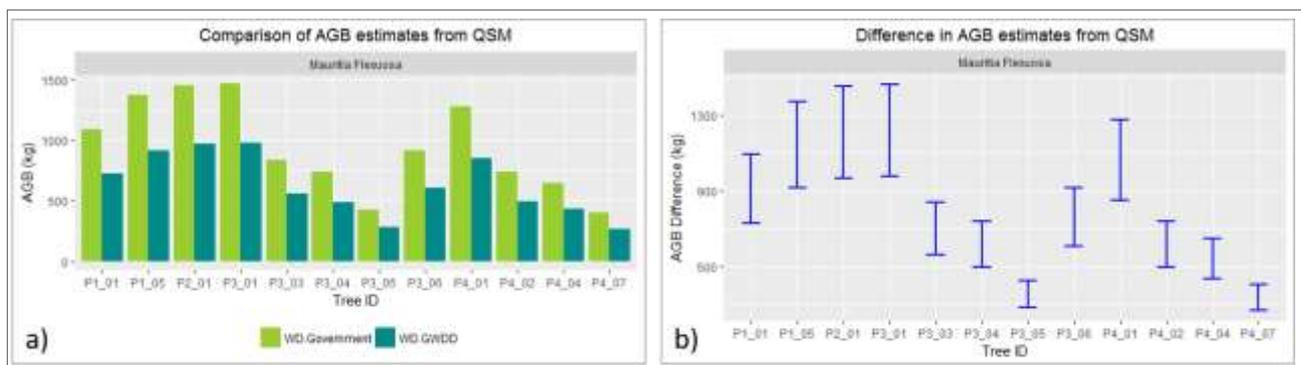


Figure 18. AGB estimates with QSM for *Mauritia flexuosa*. a) Comparison of AGB in bars showing both WDs, b) Difference between both AGB represented with error bars

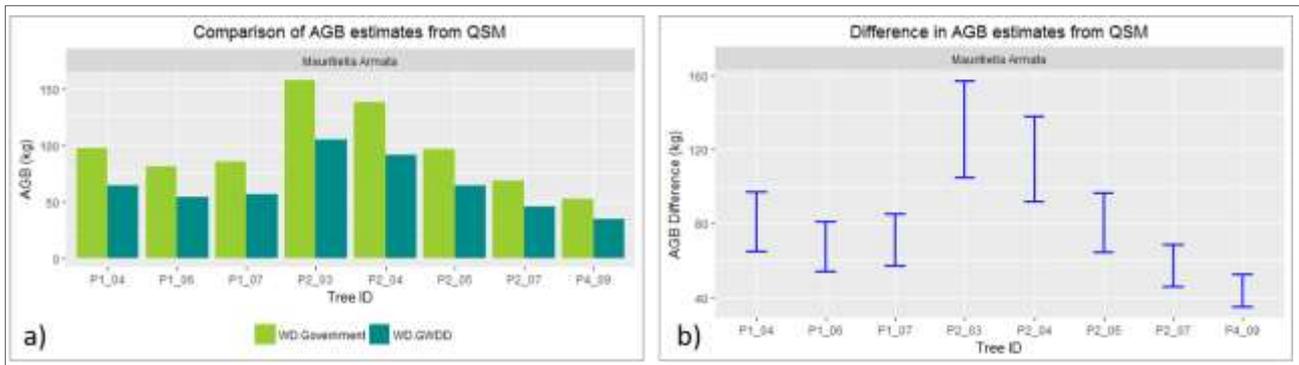


Figure 19. AGB estimates with QSM for *Mauritiella armata*. a) Comparison of AGB in bars showing both WDs, b) Difference between both AGB represented with error bars

Additionally, the number of repetitions of QSM causes a small error that also influences on these differences. Hence, for this study case without reference data, it is better to use the lowest WD ( $0.426 \text{ g/cm}^3$ ) for both palm species, which is the mean of palm family in the tropical South America region from the GWDD. However, it is important to see the comparison of this AGB outcome through QSM and the lowest WD with AGB from allometric equations in the following sections and identify possible over or underestimates in both palm species.

## 5.5 Comparison of AGB from allometric equations and with Goodman et al. (2013) results

To estimate AGB from allometric equations on *Mauritia* and *Mauritiella* palms only the stem height was considered in the regressions, instead of the tree height to avoid an overestimate caused by the leaves. The use of this stem height in allometric equations is also based on the growth pattern of palm trees, which grow more in height than in diameter, and due to their lack of branches as it is stated in Goodman et al. (2013).

Therefore, two stem heights were considered in allometric equations. One stem height was taken directly during field work and the second stem height was obtained manually from the TLS point clouds to analyse the similarity of AGB estimates. Figure 20 shows the comparison represented in bars of the AGB estimates using stem height from field inventory and TLS point clouds for both species of palms. In Figure 20a is visible that 5 palms of *Mauritia* species present a higher AGB using field data than AGB from TLS data, 6 palms have AGB from field data lower than AGB from TLS, and 1 palm has the same AGB. Overall, the variation was within 50 to 100 kg. On the other hand, for the case of

*Mauritiella*, Figure 20b shows that 3 palms obtain an AGB from Field data higher than from TLS data, in 4 palms Field-AGB was lower than TLS-AGB, and again 1 palm has the same AGB. Overall, the difference was between 2 to 5 kg.

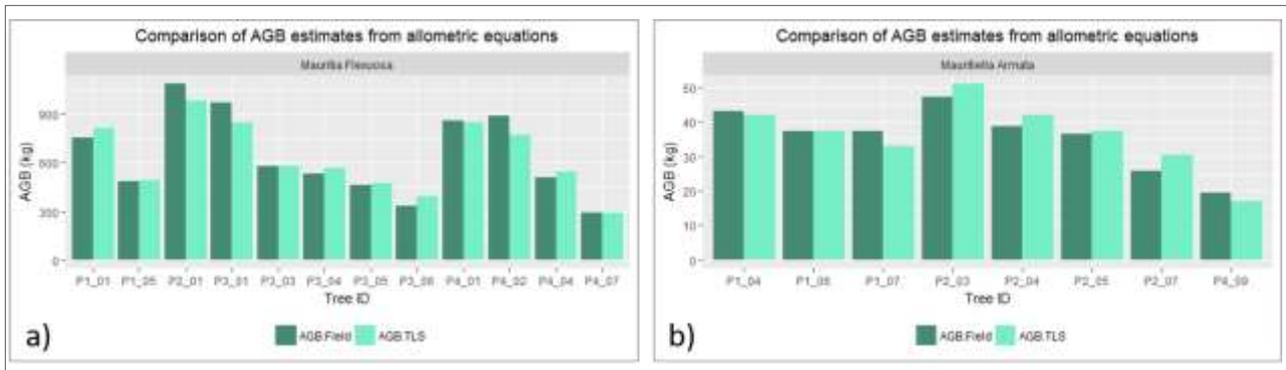


Figure 20. Comparison of AGB from allometric equations using Field and TLS data: a) *Mauritia flexuosa*, b) *Mauritiella armata*

Furthermore, in Figure 21a is demonstrated the correlation between both AGB from allometric equations for *Mauritia*. The correlation coefficient ( $r$ ) is 0.980 and coefficient of determination ( $r^2$ ) is 0.960, which means that the estimated AGB values for this species were extremely similar. On the opposite, Figure 21b shows the correlation for *Mauritiella* species, in which  $r = 0.949$  and  $r^2 = 0.901$ . For this species the similarity was also close to 1, but it was less than *Mauritia*.

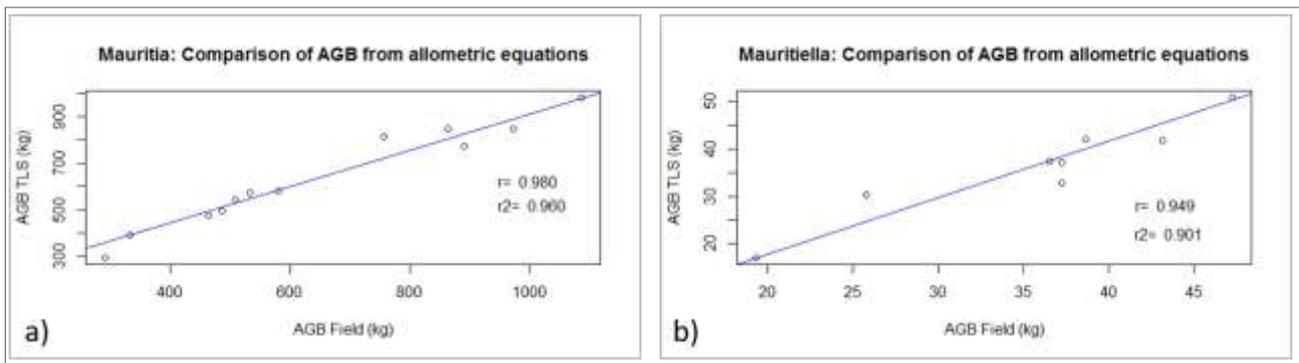


Figure 21. Correlation of AGB from allometric equations: a) *Mauritia flexuosa*, b) *Mauritiella armata*

In general, there is high likeness between both AGB estimates from allometric equations and the variance is owing to the inconsistencies in field inventory between tree height and trunk height. Due to, in most of the cases, these two measurements were exactly the same, which cannot be possible. Additionally, during the tree extraction the found palms did not have exactly the same height as the height registered in the field inventory. Moreover, the measuring techniques and different people taking and processing the data represent factors that also influence in the discrepancy of AGB

estimates. Besides, it is confirmed in previous research that measurement accuracy with TLS leads to an underestimate of 1 to 3 m (Krooks et al., 2014; Prasada et al., 2016).

Due to the absence of reference data to verify the AGB estimates, the results of AGB from allometric equations were compared visually with Goodman et al. (2013) results. Since there is no registration of data in Goodman et al. (2013) to compare with the outcomes of this study. In Figure 22 is presented the correlation between stem height and AGB. Left image shows the AGB outcomes of this research using Field and TLS data for both species. Right image, Goodman et al. (2013) presents AGB of different tree species including *Mauritia* and *Mauritiella*.

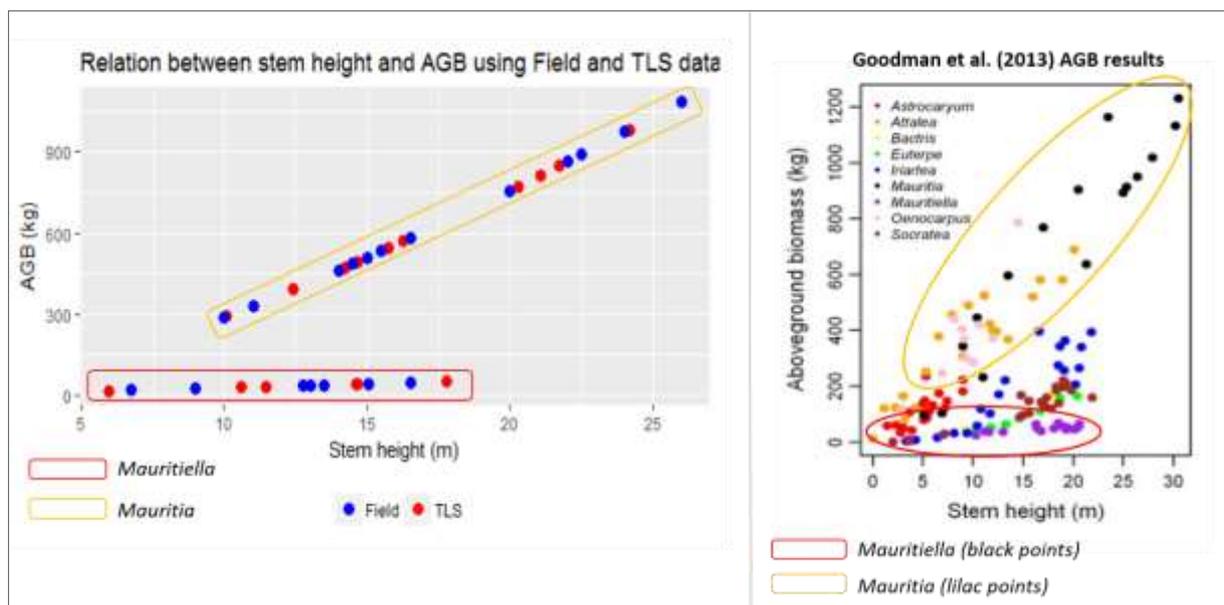


Figure 22. Comparison of AGB estimates using allometric equations with Goodman et al. (2013) AGB results. Both graphs represent the relation between stem height and AGB.

Comparing both results, the trend of each species is very similar. For instance, the AGB in *Mauritia* (yellow) is higher than in *Mauritiella* (red). And the AGB increases when the stem height becomes larger in *Mauritia* than in *Mauritiella*, due to the fact that the stem of *Mauritia* is much wider influencing a lower AGB. Furthermore, Figure 23 shows other figures presented in Goodman et al. (2013) that confirm palm trees are very light trees in comparison with coniferous trees. These images also illustrate the high correlation between stem height and AGB due to the growth pattern in palms. Moreover, if we compared the results of AGB, using allometric equations, of this research (Figure 20 and Figure 21) with the results of Goodman et al. (2013), normally, *Mauritia* with a stem diameter between 10 and 25 m have an AGB between 300 and 1 000 kg. Whereas, *Mauritiella* with a stem diameter between 5 and 15 m have an AGB between 20 and 50 kg.

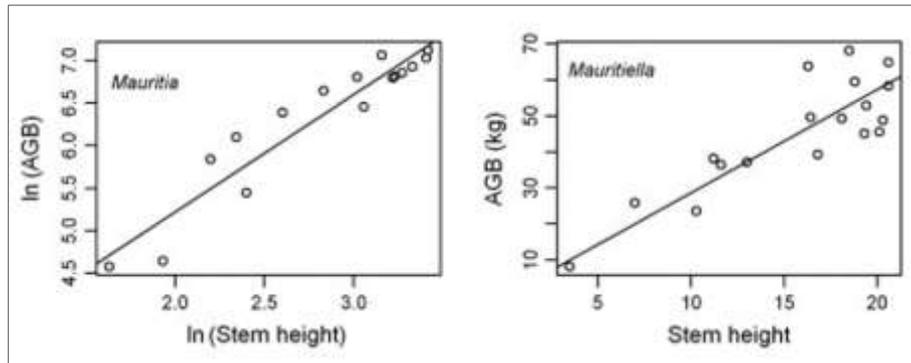


Figure 23. Goodman et al. (2013) AGB estimations for *Mauritia* and *Mauritiella*

However, the estimates obtained in this research seem to be a bit lower than Goodman's estimates. This is explained by the measuring technique. Even, when the principle of measuring stem height is the same, there can be few differences in meters at the moment to define where exactly the base and the top are.

Overall, the AGB from allometric equations which provides a better outcome is the one using TLS stem height. This is supported mainly due to the discrepancy in field inventory. Moreover, due to the differences between AGB estimates using field and TLS data, and the comparison with Goodman et al. (2013).

## 5.6 Comparison between AGB estimates from QSM and allometric equations

After choosing the best AGB estimates from QSM and allometric equations, these were contrasted to identify their variances. For QSM the best AGB estimate is using the mean WD of all palm species in the tropic from the GWDD, while for allometric equations the best AGB is with TLS data. Figure 24 presents the comparison between AGB for *Mauritia flexuosa* palms. It is showed that 3 palms have an AGB with QSM higher than AGB from allometric equations, out of which 1 palm shows a difference around 350 kg, other 2 have a difference around 200 kg and less than 50 kg. Besides, 1 palm obtained the same AGB.

Moreover, there are 8 cases with AGB from QSM lower than AGB from allometric equations, out of which 2 present a difference between 200 and 250 kg, other 3 have a difference around 100 kg and the other 3 has a difference less than 50 kg. In cases with a difference over 250 kg is because of the fewer number of cylinders selected to calculate the volume of the stem. Which is explained by the effect of leaves form of *Mauritia* on QSM, causing a not entirely accurate model neither branch order. At the same time, this affects the stem volume calculation, causing the AGB underestimate. Generally, the

results are quite similar, demonstrating that this WD gives acceptable estimates and can be useful for this type of palm species.

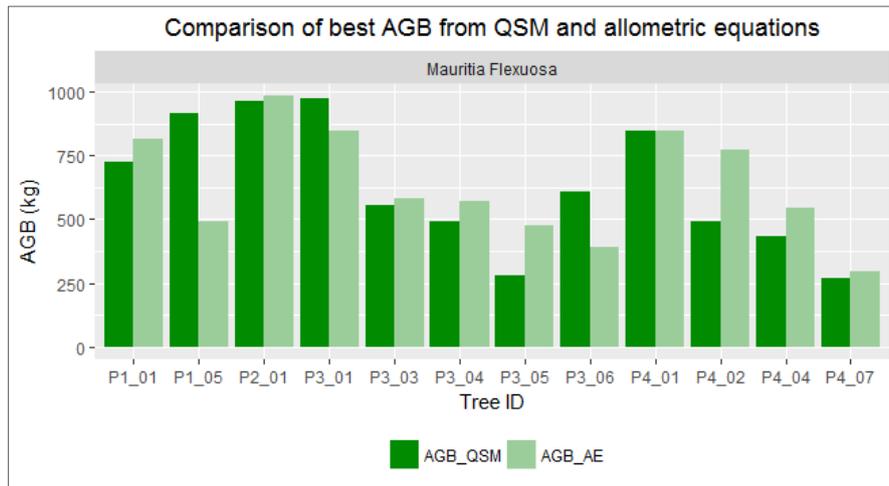


Figure 24. *Mauritia flexuosa*: Comparison of AGB estimates from QSM and allometric equations

On the other hand, Figure 25 shows the results in the case of *Mauritiella*, which presents a completely different situation. Because the AGB using the mean of WD from the GWDD is highly overestimated in comparison with AGB from allometric equations. This overestimate is generally between 10 to 40 kg. Therefore, it is confirmed that this WD is not appropriate for this palm species due to its form. Since this species characterizes by a narrow and large stem, requires a lower WD. Furthermore, the higher dissimilarity of AGB is an effect of a larger number of cylinders selected for stem volume to estimate AGB. Thus, in contrast with *Mauritiella*, this larger number of cylinders causes an overestimated AGB.

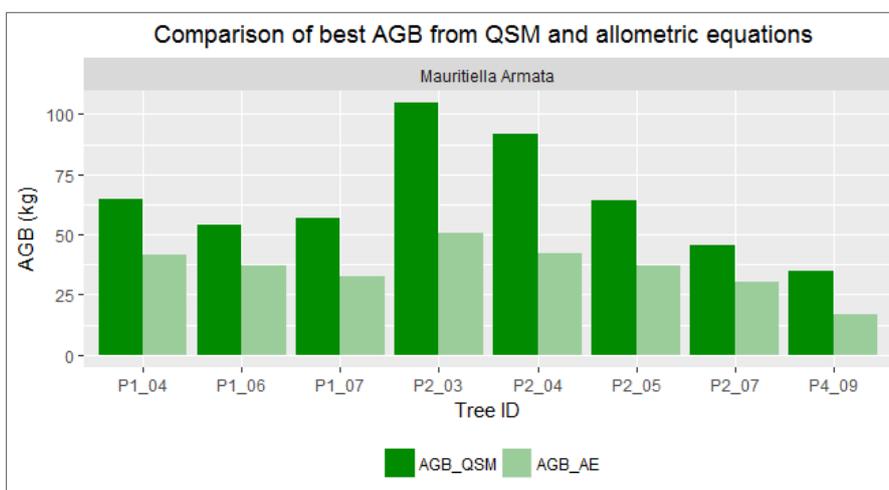


Figure 25. *Mauritiella armata*: Comparison of AGB estimates from QSM and allometric equations

To continue with the results about likeliness of AGB, it is important to know the correlation coefficient ( $r$ ) and coefficient of determination ( $r^2$ ) between these AGB estimates. Figure 26 shows the correlation in *Mauritia* cases, in which  $r = 0.692$  and  $r^2 = 0.479$ . From the distribution of points far from the line and the low coefficient of determination is deduced that the correlation is not strong due to the variety in AGB estimates from both methods (QSM and allometric equations).

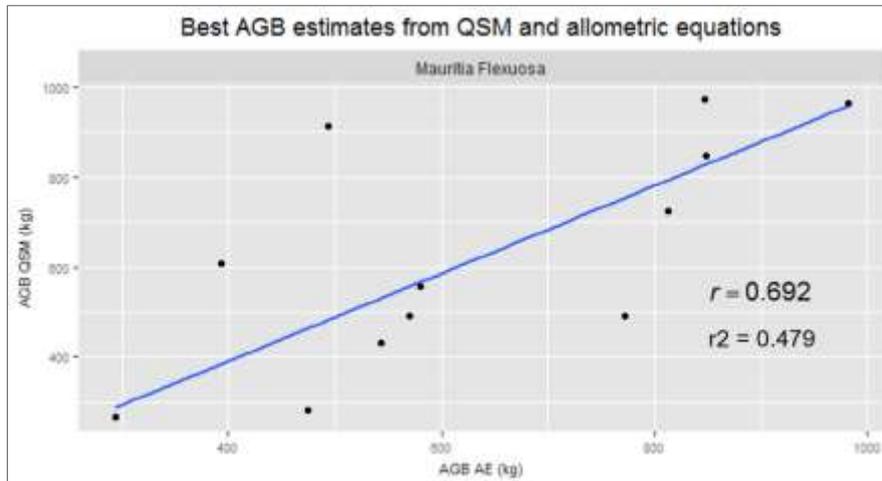


Figure 26. *Mauritia flexuosa*: Correlation of best AGB estimates from QSM and allometric equations

On the contrary, as it is showed in Figure 27, the correlation between *Mauritiella armata* AGB estimates is strong having high values in the coefficients ( $r = 0.890$  and  $r^2 = 0.793$ ). The points are closer to the line which represents correlation 1. This result is explained because there is trend in the estimates similar to a bell curve. Due to the AGB from QSM turned out to be higher than AGB from allometric equations in all the cases as it is presented in Figure 25.

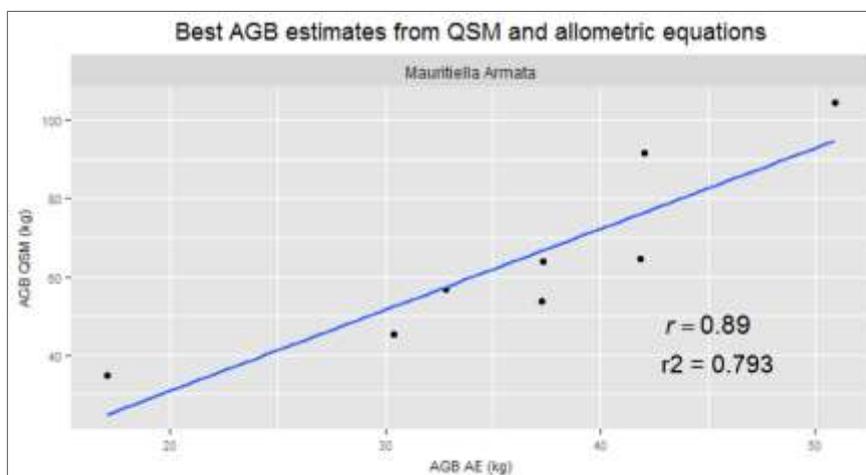


Figure 27. *Mauritiella armata*: Correlation of best AGB estimates from QSM and allometric equations

In general, AGB estimates from QSM and allometric equations in *Mauritia* are alike. While, AGB in *Mauritiella* is unlike with a very noticeable overestimate from AGB with QSM. However, the correlation in *Mauritia* is not strong due to a huge variety in the estimates. Whereas, the correlation in *Mauritiella* is strong because of the similarity between the estimates.

## 6. Discussion

---

### 6.1 Difficulties in manual tree extraction

Tree extraction is the first step in the whole QSM process to estimate AGB. Each individual palm tree extraction needs to be done manually since there is still no feasible and accurate automatization at this stage. The detail in TLS point clouds by the number of scans in field allowed to obtain the 20 palm trees. However, this detail can be affected by the density of vegetation, the shape of trees, the distance to the scanners and the range of the scan. Furthermore, even when fieldwork can be a hard work, it is important to make clear and high-quality field notes in order to find the palm trees easier in the scans, because sometimes different people take and process the data.

One of the tasks that took more time than expected was the identification of palm trees registered in the field inventory within the point clouds. This is due to the shift at the moment of scanning during fieldwork which influenced the distance and azimuth of the entire plot. It was not clear enough how these measurements were taken and how to adjust the point cloud plot for a quicker identification which meant a time-consuming step. It is stated in the literature reviewed that tree extraction is still a non-automatized and time-consuming process. Nevertheless, I consider that to match field with TLS data in less time can be done with precise field data in combination with tools of the RiScan Pro software, which are very helpful in the identification of individual objects.

Furthermore, in the case of palm trees the DBH is not taken in field inventory as in the case of coniferous trees because its diameter does not change highly in palms, however this tree measurement could be helpful to use it together with the distance and azimuth angle. Because, when the user selects a small range of the lowest heights with the height tool, only spread circles are displayed and from these circles is easier to measure their diameter using the rule tool (Figure 28). On the contrary, the identification of palm by height takes more time because after the distance and azimuth are identified it is time to verify the palm height. But, going up to higher heights the vegetation becomes denser and it is easier to lose or confuse the palm that the user was looking for, especially for palms higher than 15 meters.

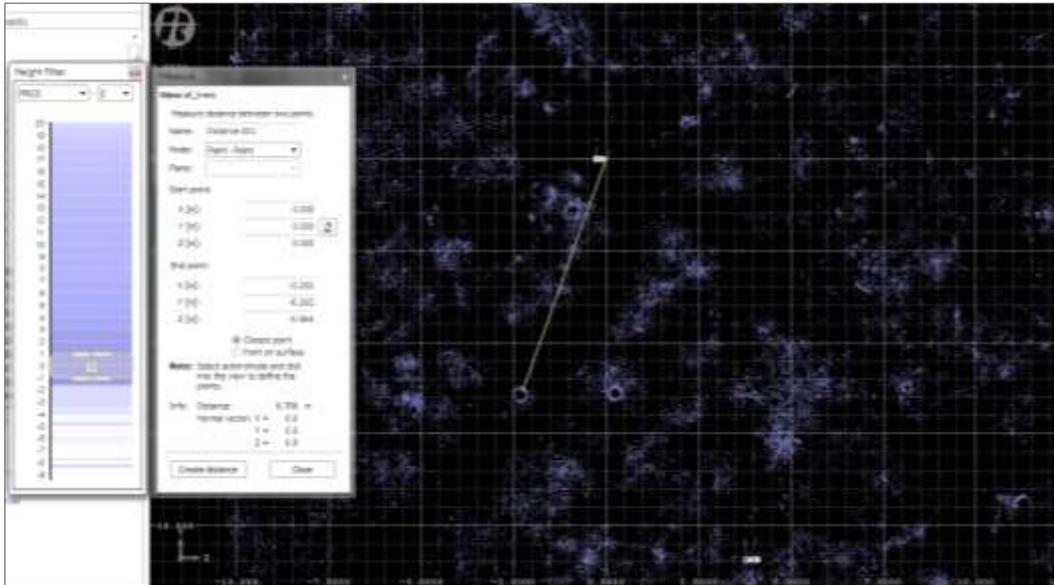


Figure 28. Display of point cloud at 1 meter of height. Each circle is a tree and its diameter can be measured with the rule tool.

## 6.2 Significant elements to enhance the Quantitative Structure Model

To obtain accurate QSM the detail of point clouds in combination with appropriate values in the parameters of the algorithm are determinant. The level of detail of TLS point clouds using 10 scans was acceptable, but not the whole plot has the same definition. As a result of this difference in level of detail there was a variety in the definition of individual palms. Actually, during the search of the selected palm trees there were some palms identified which had a higher point density, but these could not be considered for the modelling because these were not registered in the field inventory. However, as an extra analysis these palm trees with high point density, even when they are not part of the inventory, can be considered to estimate AGB only using the measurements from the TLS data and compare them with the data obtained from this research or with Goodman et al. (2013) to verify if there is any improvement.

Regarding the parameters of the QSM algorithm developed by Raumonen et al. (2013), in this study an assessment was done to decide the most appropriate values of each one and only apply a variation in the parameter *PatchDiam2Min* to do the sensitivity analysis. Though, for further analysis it is recommendable to make more assessments changing other parameters and see the results of the 3D palm tree models, especially playing with the parameters of the second cover which are the ones with has more influence in the results. Consequently, according to the results the best number was 0.06 m for *PatchDiam2Min*. Therefore, an increase in the values of *PatchDiam2Min*, *PatchDiam2Max* and

*BallRad2* parameters could improve the fit of palm model in the point cloud. Moreover, even when the algorithm models the leaves of the palm as branches, the 3D model can be also improved at the canopy.

Furthermore, it is important to consider that values on each parameter of the QSM algorithm will give different models depending on the species and the detail of point cloud. For this reason, another recommendation is to run models with different values for each palm species. For instance, for the species *Mauritia flexuosa* the number of the second cover parameters mentioned before can be higher because its stem diameter is wider and its fronds are longer. On the other hand, for the species *Mauritiella armata* the values can be higher than the ones used for this study, but less than the new ones for *Mauritia* due to its narrow stem and fronds are smaller.

### **6.3 Subjectivity of visual sensitivity analysis**

The next stage to assess AGB from 3D palm models from QSM in this study was to decide a method to evaluate the total amount of models and to find which values of the changeable parameter modelled the best palm tree structure of each of the 20 palms analyzed in this research. Therefore, a visual analysis was carried out with a personal evaluation grading system, generally, based on the straightness of cylinders and coverage of the stem diameter. It is well-known that a visual assessment can be very subjective because one model that seems accurate for one person is not precise for another one.

Therefore, this grading system was tested with some colleagues to see if it was appropriate and understandable to decide the best value of *PatchDiam2Min* parameter changed in the models. And at the same time to compare the results from the testers with the ones obtained in this research. Furthermore, to support the feasibility of the grading system for the visual assessment it was suitable to do the tests with people who understand the aim of this research and with a remote sensing background to be able to test more adequately.

Moreover, as a recommendation to improve the assessment of the 3D palm models from QSM, instead of using a visual (qualitative) method it is possible to try quantitative methods such as volume estimate, total of cylinders, and tree height. Because the outcomes of QSM provide data of each cylinder from which statistics can be operated, and compare these results. The volume from the entire model or until a define branch order also can be calculated and compared to see over or underestimations.

#### 6.4 Missing elements to estimate accurately AGB from QSM and validation

After the selection of the best values of the parameters for QSMs per each of the 20 palm trees, I applied the Smalian's formula (Ministry of Forest, 2011) to the entire models to calculate the volume of the cylinders. Afterwards, I only considered the volume of the cylinders that covered the trunk. Next, I multiplied this volume of the trunk by the wood density of palm trees to obtain the AGB. This study used two wood densities, one taken from a document of the Peruvian government about carbon estimates in the Peruvian forests (Ambiente, 2014). The other density was the mean of the wood densities of the palm species in South America within the tropical region registered in the GWDD (Zanne et al., 2009).

The performance of AGB estimates using QSM was easy to apply following the mass formula, in which the volume was obtained from the cylinders of the QSMs and the WD values. However, the problem is that there are not available WDs for the two species of palms analyzed in this research. The results showed that the WD from the Peruvian government highly overestimates the AGB. While the use of mean WD from GWDD is not the best, but it is acceptable for *Mauritia*. On the other hand, this WD is not acceptable for *Mauritiella*. Though, according to the expert R. Goodman, the use of the mean of wood densities from the GWDD was not recommendable since the WD in palms varies hugely per species.

Additionally, these values are not easy to validate due to the absence of reference data to compare the results with. Therefore, the feasible choice to assess the results of AGB from QSM was the comparison with results from another method, which is allometric equation. In fact, the decision to consider volume only from the trunk of palm trees was based on the structure of these equations to make the results more comparable and avoid higher overestimates. Moreover, due to the fact that the research of Goodman et al. (2013) had reference data of the same palm species, the outcomes of AGB-QSM were compared with the results from this research. Nonetheless, the differences with Goodman were higher, which is explained by the sum of all this factors that influenced in the accuracy of AGB using QSM.

As a recommendation, there is a clear necessity of wood density factors for the palm species *Mauritia* and *Mauritiella* to obtain accurate outcomes using QSM without over or underestimates, due to the importance of these species as dominants within the Peruvian amazon and at the same time of these Amazonia as part of the PSF in the tropics for further quantification and analysis of carbon sinks. Furthermore, to improve the assessment of AGB it is relevant to use reference data to validate the estimates, considering the compatibility in the measuring methods of palm tree elements.

## 6.5 Discrepancy in field and TLS measurements used in allometric equations to estimate AGB

To have elements to assess the AGB estimates from QSM it was necessary to compare the results with estimates from allometric equations. Due to the fact that this study is based on two palm species, the allometric equations for the same species proposed by Goodman et al. (2013) were used to calculate the AGB. These allometric equations needed the stem height which is one of the measurements taken in the field. Furthermore, to analyze the similarity with the stem height from the TLS point clouds, I manually measured this height in the point clouds using point to see their Z values. Then, I subtracted the Z value of the bottom point from the Z top point.

It was expected to have a variety in the stem height measurements between field and TLS data, nevertheless the difference did not show a trend. This is explained because the field data presented the same values for tree height and stem height, being this the first factor of dissimilarity. Additionally, this tree height together with distance and azimuth was used to find the individual palm trees in the point clouds. But, the palms founded did not have the same height, thus another variation factor was added. Overall, even with this differences in stem height the AGB estimate from allometric equations were not huge. On the other hand, these AGB estimates in comparison with the AGB from the QSM showed a higher discrepancy, especially in the case of *Mauritiella*.

Regarding the comparison with results of Goodman et al. (2013), in general the AGB estimates of this study were very close to Goodman AGB estimates. It was not possible to make a comparison quantitatively since this research only provides the results in graphs. Nonetheless, the same graphs were made in this study to make a visual comparison and the AGB estimates show similar trend.

As a suggestion, another AGB estimate can be made and compared using the stem height obtained from the QSMs, since the output files have this information, which is calculated as the summary of heights of the cylinders. However, from my own insight it is important to take into account that there is high variation in the palm tree 3D models, which, surely, will influence the AGB outcomes.

## 7. Conclusions

The criteria to evaluate 3D palm tree models obtained by QSM is a visual assessment that focuses only on the model of the stem. Due to the lack of branches and growth pattern—grow more in height than diameter—as its typical characteristics. Therefore, this visual analysis evaluated the adjustment of the cylinders along the stem, their straightness and the fit in the diameter of the trunk delineated by the point cloud. In this study the value 0.06 m of *PatchDiam2Min* parameter fits the best palm tree model. The quality of this 3D model depends on the point cloud density, the form of the palm, and the values assigned to the parameters of QSM algorithm

The stem QSM and the lowest WD (426 kg/m<sup>3</sup>) used in this research gave an adequate AGB estimate for *Mauritia*. Due to this WD (mean of palms in the tropic from GWDD) is acceptable for this species with wider stem. This in combination with the 3D model of the stem using the best value of *PatchDiam2Min* allows an accurate volume estimate. On the other hand, the same WD is not sufficient for *Mauritiella*. Because of its narrow stem the AGB is overestimated. However, the QSM of the stem is adequate for the volume estimate. In both species, the higher the value for *PatchDiam2Min* the better the model of the stem is.

AGB estimates from allometric equations using stem height from field and TLS are very similar in both palm species. Overall, in *Mauritia*, the variances were between 50 to 100 kg and the coefficients were  $r = 0.980$  and  $r^2 = 0.960$ . Whereas, in *Mauritiella*, the differences were from 5 to 10 kg and coefficients were  $r = 0.949$  and  $r^2 = 0.901$ . Therefore, it is confirmed that AGB estimates are hugely alike. When palm tree measurements are used in allometric equations, the variances are mainly due to the different measuring techniques in field and from point clouds and discrepancy in fieldwork data. Additionally, it is confirmed that TLS leads to an underestimate of 2 to 3 m.

AGB estimates from QSM and allometric equations are very similar in *Mauritia*, but not much similar in *Mauritiella*. For *Mauritia*, AGB estimates show variances because in some cases AGB with QSM is higher than AGB from allometric equations or vice versa. But, the difference in kg is not that high which mostly varies from 50 to 250 kg. Furthermore, this variations cause a low correlation, having  $r = 0.692$  and  $r^2 = 0.479$ . On the contrary, for *Mauritiella*, there is a trend in the variety of AGB due to AGB from QSM is higher than AGB from allometric equations in all the cases with differences between 10 to 40 kg. Thus, this trend causes a higher correlation, having  $r = 0.890$  and  $r^2 = 0.793$ .

## 8. References

- Ambiente, M. del. (2014). *Estimación de los contenidos de carbono de la biomasa aérea en los bosques de Perú* (1ra Ed.). Lima, Perú: Ministerio del Ambiente. Retrieved from [http://www.bosques.gob.pe/archivo/libro\\_carbono.pdf](http://www.bosques.gob.pe/archivo/libro_carbono.pdf)
- Baker, T. R., Phillips, O. L., Malhi, Y., Almeida, S., Arroyo, L., Di Fiore, A., Erwin, T., Killen, T. J., Laurance, S. G., Laurance, W. F., Lewis, S. L., Lloy, J., Monteagudo, A., Neil, D. A., Patino, S., Pitman, N. C. A., Silva, M., Natalino, J., Vasquez Martinez, R. (2004). Variation in wood density determines spatial patterns in Amazonian forest biomass. *Global Change Biology*, 10(5), 545–562. <https://doi.org/10.1111/j.1365-2486.2004.00751.x>
- Balslev, H., Grandez, C., Zambrana, P., Møller, N. Y., Lykke, H., & Sandie, A. L. (2008). Palmas (Arecaceae) útiles en los alrededores de Iquitos, Amazonía Peruana. *Rev. Peru. Biol.*, 15(1), 121–132. Retrieved from [http://www.scielo.org.pe/scielo.php?pid=S1727-99332008000000014&script=sci\\_arttext](http://www.scielo.org.pe/scielo.php?pid=S1727-99332008000000014&script=sci_arttext)
- Baskerville, G. L. (1972). Use of Logarithmic Regression in the Estimation of Plant Biomass. *Canadian Journal of Forestry*, 2, 49–53. <https://doi.org/Export Date 18 February 2014>
- Bauwens, S., Bartholomeus, H., Calders, K., & Lejeune, P. (2016). Forest Inventory with Terrestrial LiDAR: A Comparison of Static and Hand-Held Mobile Laser Scanning. *Forests*, 7(6), 127. Retrieved from <http://www.mdpi.com/1999-4907/7/6/127>
- Brown, S., Sathaye, J., Cannell, M., & Kauppi, P. E. (1996). Mitigation of carbon emissions to the atmosphere by forest management. Commonwealth Forestry Review. *Commonwealth Forestry Review*, 75(January), 80–91.
- Calders, K., Newnham, G., Burt, A., Murphy, S., Raunonen, P., Herold, M., Culvenur, D., Avitabile, V., Disney, M., Armston, J., Kaasalainen, M. (2015). Nondestructive estimates of above-ground biomass using terrestrial laser scanning. *Methods in Ecology and Evolution*, 6(2), 198–208. <https://doi.org/10.1111/2041-210X.12301>
- Chave, J., Andalo, C., Brown, S., Cairns, M. A., Chambers, J. Q., Eamus, D., Fölster, H., Fromard, F., Higuchi, N., Kira, T., Lescure, J. P., Nelson, B. W., Ogawa, H., Puig, H., Riéra, B., Yamakura, T. (2005). Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia*, 145(1), 87–99. <https://doi.org/10.1007/s00442-005-0100-x>
- Côté, J.-F., Fournier, R. A., & Egli, R. (2011). An architectural model of trees to estimate forest structural attributes using terrestrial LiDAR. *El Sevier-Environmental Modelling & Software*, 26, 761–777. Retrieved from <http://www.sciencedirect.com/science/article/pii/S1364815210003294>
- De Peru.com - Portal de Internet. (2017). Retrieved January 22, 2017, from <http://www.deperu.com/esparcimiento/centros-recreacionales/complejo-turistico-de-quistococha-2639>
- Drake, J. B., Knox, R. G., Dubayah, R. O., Clark, D. B., Condit, R., Blair, J. B., & Hofton, M. (2003). Above-ground biomass estimation in closed canopy Neotropical forests using lidar remote sensing: Factors affecting the generality of relationships. *Global Ecology and Biogeography*, 12(2), 147–159. <https://doi.org/10.1046/j.1466-822X.2003.00010.x>
- Draper, F. C., Roucoux, K. H., Lawson, I. T., A Mitchard, E. T., Honorio Coronado, E. N., Lähteenoja, O., ... Baker, T. R. (2014). The distribution and amount of carbon in the largest peatland complex in Amazonia. *Environmental Research Letters*, 9, 124017. <https://doi.org/10.1088/1748-9326/9/12/124017>

- Dutrieux, L. P. (2016). *Multidimensional remote sensing based mapping of tropical forests and their dynamics. Laboratory of Geo-Information Science and Remote Sensing*. Wageningen University and Research Centre, PhD Thesis, Wageningen, the Netherlands.
- Frangi, J. L., & Lugo, A. E. (1985). Ecosystem Dynamics of a Subtropical Floodplain Forest. *Ecological Monographs*, 55(3), 351–369. <https://doi.org/10.2307/1942582>
- Freitas Alvarado, L., & Flores, H. (2015). Condición silvicultural de la palmera *Mauritia flexuosa* L.f. en el ecosistema “Aguajal” de Parinari, Loreto, Perú. *Folia Amazónica*, 24(2), 155–162. Retrieved from <http://revistas.iiap.org.pe/index.php/foliaamazonica/article/view/73/122>
- Freitas Alvarado, L., Otárola Acevedo, E., del Castillo Torres, D., Linares Bensimón, C., Martínez Dávila, P., & Malca Salas, G. A. (2006). *Servicios ambientales de almacenamiento y secuestro de carbono del ecosistema aguajal en la Reserva Nacional Pacaya Samiria, Loreto - Perú* (Second Edi). Iquitos, Perú: Dominus Publicidad E.I.R.L. Retrieved from [http://aplicaciones.cientifica.edu.pe/repositorio/catalogo/\\_data/87.pdf](http://aplicaciones.cientifica.edu.pe/repositorio/catalogo/_data/87.pdf)
- GEOSUR. (n.d.). GEOSUR La Red Geoespacial de América Latina y el Caribe. Retrieved January 19, 2017, from <https://www.geosur.info/geosur/index.php/en/available-data>
- Gilmore, M. P., Endress, B., & Horn, C. M. (2013). The socio-cultural importance of *Mauritia flexuosa* palm swamps (aguajales) and implications for multi-use management in two Maijuna communities of the Peruvian Amazon. *Journal of Ethnobiology and Ethnomedicine*, 9(1), 29. <https://doi.org/10.1186/1746-4269-9-29>
- Gonzalez de Tanago, J., Bartholomeus, H., Shijo, J., Herold, M., Avitabile, V., Goodman, R., Raumonon, P., Burt, A. (2015). Terrestrial LiDAR and 3D tree Quantitative Structure Model for quantification of aboveground biomass loss from selective logging in a tropical rainforest of Peru. In S. Durrieu, I.-U. TETIS, C. Véga, IGN, & LIF (Eds.), *Proceedings of SilviLaser 2015* (pp. 119–121). La Grande Motte, France. Retrieved from [https://silvilaser2015.teledetection.fr/files/Proceedings\\_Silvilaser\\_22\\_09\\_2015\\_2.pdf](https://silvilaser2015.teledetection.fr/files/Proceedings_Silvilaser_22_09_2015_2.pdf)
- Goodman, R., Phillips, O. L., del Castillo Torres, D., Freitas Alvarado, L., Tapia Cortese, S., Monteagudo, A., & Baker, T. R. (2013). Amazon palm biomass and allometry. *Forest Ecology and Management*, 310, 994–1004. Retrieved from [http://www.rainfor.org/upload/publication-store/2013/Goodman/Goodman\\_et\\_al\\_Amazon\\_palm\\_biomass\\_allometry\\_FEM\\_2013.pdf](http://www.rainfor.org/upload/publication-store/2013/Goodman/Goodman_et_al_Amazon_palm_biomass_allometry_FEM_2013.pdf)
- Hackenberg, J., Morhart, C., Sheppard, J., Spiecker, H., & Disney, M. (2014). Highly accurate tree models derived from terrestrial laser scan data: A method description. *Forests*, 5(5), 1069–1105. <https://doi.org/10.3390/f5051069>
- Hergoualc’h, K., Gutierrez-Velez, V. H., van Lent, J., & Verchot, L. V. (2016). Characterizing peat palm forest degradation in the Peruvian Amazon from space and on the ground. Vienna, Austria: European Geosciences Union General Assembly 2016. Retrieved from <http://meetingorganizer.copernicus.org/EGU2016/EGU2016-9431.pdf>
- Holopainen, M., Vastaranta, M., Kankare, V., Raty, M., Vaaja, M., Liang, X., Yu, X., Hyypä, J., Hyypä, H., Viitala, R., Kaasalainen, S. (2011). Biomass estimation of individual trees using stem and crown diameter TLS measurements. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XXXVIII-5(W12), 31–38. <https://doi.org/10.1016/j.isprsjprs.2012.10.003>
- Hopkinson, C., Chasmer, L., Young-Pow, C., & Treitz, P. (2004). Assessing forest metrics with a ground-based scanning lidar. *Canadian Journal of Forest Research*, 34(3), 573–583. <https://doi.org/10.1139/x03-225>
- Kaasalainen, S., Krooks, A., Liski, J., Raumonon, P., Kaartinen, H., Kaasalainen, M., ... Mäkipää, R.

- (2014). Change detection of tree biomass with terrestrial laser scanning and quantitative structure modelling. *Remote Sensing*, 6(5), 3906–3922. <https://doi.org/10.3390/rs6053906>
- Kahn, F., Mejía, K., Moussa, F., & Gómez, D. (1993). *Mauritia flexuosa*, la más acuática de la palmeras amazónicas. In *Las plantas vasculares en las aguas continentales del Perú* (pp. 287–308). Lima, Perú: IFEA. Retrieved from [http://horizon.documentation.ird.fr/exl-doc/pleins\\_textes/divers09-06/39108.pdf](http://horizon.documentation.ird.fr/exl-doc/pleins_textes/divers09-06/39108.pdf)
- Kankare, V., Holopainen, M., Vastaranta, M., Puttonen, E., Yu, X., Hyypä, J., Vaaja, M., Hyypä, H., Alho, P. (2013). Individual tree biomass estimation using terrestrial laser scanning. *ISPRS Journal of Photogrammetry and Remote Sensing*, 75, 64–75. <https://doi.org/10.1016/j.isprsjprs.2012.10.003>
- Krooks, A., Kaasalainen, S., Kankare, V., Joensuu, M., Raunonen, P., & Kaasalainen, M. (2014). Predicting tree structure from tree height using terrestrial laser scanning and quantitative structure models. *Silva Fennica*, 48(2), 11. Retrieved from <http://dx.doi.org/10.14214/sf.1125>
- Kurnianto, S., Warren, M., Talbot, J., Kauffman, B., Frohking, S., & Murdiyarso, D. (2013). Long-term carbon accumulation in tropical peat swamp forests in Indonesia. New Hampshire, USA: University of New Hampshire. Retrieved from [http://posters.unh.edu/media/uploads/originals/2013/04/18/skurnianto\\_AGU\\_poster\\_kurnianto\\_rev.pdf](http://posters.unh.edu/media/uploads/originals/2013/04/18/skurnianto_AGU_poster_kurnianto_rev.pdf)
- Lau Sarmiento, A. I. (2014). *Using T-LiDAR as an Alternative Measurement Technique for Plant-Scaling Modelling in Tropical Forest*. Laboratory of Geo-Information Science and Remote Sensing. Wageningen University and Research Centre, MSc Thesis, Wageningen, the Netherlands.
- Lau Sarmiento, A. I., Bartholomeus, H., Herold, M., Martius, C., Malhi, Y., Patrick Bentley, L., ... Raunonen, P. (2015). Application of terrestrial LiDAR and modelling of tree branching structure for plantscaling models in tropical forest trees. In *Proceedings of SilviLaser 2015* (pp. 96–98). La Grande Motte, France.
- Manzi, M., & Coomes, O. T. (2009). Managing Amazonian palms for community use: A case of aguaje palm (*Mauritia flexuosa*) in Peru. *Forest Ecology and Management*, 257(2), 510–517. <https://doi.org/10.1016/j.foreco.2008.09.038>
- Marvin, D. C., Asner, G. P., Knapp, D. E., Anderson, C. B., Martin, R. E., Sinca, F., & Tupayachi, R. (2014). Amazonian landscapes and the bias in field studies of forest structure and biomass. *Proceedings of the National Academy of Sciences of the United States of America*, 111(48). Retrieved from <http://doi.org/10.1073/pnas.1412999111>
- Ministry of Forest, L. and N. (2011). Smalian's formula. In *Scaling Manual* (pp. 4-11). British Columbia. Retrieved from <https://www.for.gov.bc.ca/ftp/hva/external!/publish/Web/Manuals/Scaling/2011/Scaling2011NovMaster.pdf>
- Molina, P. X., Asner, G. P., Farjas Abadía, M., Ojeda Manrique, J. C., Sánchez Diez, L. A., & Valencia, R. (2016). Spatially-explicit testing of a general aboveground carbon density estimation model in a western Amazonian forest using airborne LiDAR. *Remote Sensing*, 8(1). <https://doi.org/10.3390/rs8010009>
- Murdiyarso, D., Hergoualc'h, K., & Verchot, L. V. (2010). Opportunities for reducing greenhouse gas emissions in tropical peatlands. *Proceedings of the National Academy of Sciences of the United States of America*, 7(46), 19655–19660. Retrieved from <http://www.pnas.org/cgi/doi/10.1073/pnas.0911966107>

- Padoch, C. (1988). Aguaje (*Mauritia flexuosa*) in the Economy of Iquitos, Peru. *Advances in Economic Botany*, 6, 214–224.
- Palmer, M. W., Sullivan, F. B., Ducey, M., & Herrick, C. (2016). Estimating Tropical Forest Structure Using a Terrestrial Lidar. *PLOS ONE*, 11(4). Retrieved from <http://doi.org/10.1371/journal.pone.0154115>
- Peñuela Mora, M. C. (2014). *Understanding Colombian Amazonian White Sand Forests*. Utrecht University, MSc Thesis.
- Posa, M. R. C., Wijedasa, L. S., & Corlett, R. T. (2011). Biodiversity and Conservation of Tropical Peat Swamp Forests. *Bioscience*, 61(1), 49–57. Retrieved from <http://bioscience.oxfordjournals.org>
- Prasada, O. P., Hussinb, Y. A., Weirb, M., Karnac, J. C., & Yogendra, K. (2016). Derivation of forest inventory parameters for carbon estimation using terrestrial LIDAR. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLI-B8, 677–684. Retrieved from <http://www.int-arch-photogramm-remote-sens-spatial-inf-sci.net/XLI-B8/677/2016/isprs-archives-XLI-B8-677-2016.pdf>
- Raumonen, P. (2015). Quantitative structure tree models from terrestrial laser scanner data. In *Proceedings of SilviLaser 2015* (pp. 32–34). La Grande Motte, France.
- Raumonen, P., Casella, E., Calders, K., Murphy, S., Akerblom, M., & Kaasalainen, M. (2015). Massive-scale tree modelling from TLS data. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, II-3/W4, 189–196. Retrieved from <http://www.isprs-ann-photogramm-remote-sens-spatial-inf-sci.net/II-3-W4/189/2015/isprsannals-II-3-W4-189-2015.pdf>
- Raumonen, P., Kaasalainen, M., Åkerblom, M., Kaasalainen, S., Kaartinen, H., Vastaranta, M., Holopainen, M., Disney, M., Lewis, P. (2013). Fast Automatic Precision Tree Models from Terrestrial Laser Scanner Data. *Remote Sensing*, 5(2), 491–520. <https://doi.org/10.3390/rs5020491>
- Rich, P. M. (1987). Mechanical Structure of the Stem of Arborescent Palms. *Botanical Gazette*, 148(1), 42–50. <https://doi.org/10.1086/337626>
- Rich, P. M., Helenurm, K., Kearns, D., Morse, S. R., Palmer, M. W., & Short, L. (1986). Height and Stem Diameter Relationships for Dicotyledonous Trees and Arborescent Palms of Costa Rican Tropical Wet Forest. *Bulletin of the Torrey Botanical Club*, 113(3), 241–246. Retrieved from <http://www.jstor.org/stable/2996362>
- Rivadeneira, M. G. (1974). Estudio sobre la densidad de poblaciones de aguaje (*Mauritia* sp.) en Tingo María-Perú. *Revista Forestal Del Perú*, 5(1–2), 1–11.
- Schlegel, B. (2001). *Estimación de la biomasa y carbono en bosques del tipo forestal siempreverde*. Valdivia, Chile. Retrieved from [http://www.uach.cl/procarbono/pdf/simposio\\_carbono/45\\_schlegel.PDF](http://www.uach.cl/procarbono/pdf/simposio_carbono/45_schlegel.PDF)
- Vashum, K. T., & Jayakumar, S. (2012). Methods to Estimate Above-Ground Biomass and Carbon Stock in Natural Forests - A Review. *Journal of Ecosystem & Ecology*, 2(4), 7. Retrieved from <https://www.omicsonline.org/methods-to-estimate-above-ground-biomass-and-carbon-stock-in-natural-forests-a-review-2157-7625.1000116.php?aid=8804>
- Vazirabad, Y. F., & Karslioglu, M. O. (2011). Lidar for biomass estimation. In D. Matovic (Ed.), *Biomass - detection, production and usage* (pp. 3–25). InTech. <https://doi.org/10.5772/973>
- Zanne, A. E., Lopez-Gonzalez, G., Coomes, D. A., Ilic, J., Jansen, S., Lewis, S. L., ... Chave, J. (2009).

Global wood density database. *Dryad*, 235(February), 33. <https://doi.org/10.5061/dryad.234>

# 9. Appendices

## Appendix 1. Tree extraction filling form

(These three separate tables were part of one big table, following the order as these tables are presented)

FIELD DATA					
Plot	Species	Height (m)	Trunk Length(m)	Distance	Azimuth
1	Mauritia Flexuosa	20	20	5	220
2	Mauritia Flexuosa	26	26	9.3	89
3	Mauritia Flexuosa	15.5	15.5	5.9	293
4	Mauritia Flexuosa	22	22	6.1	238
...	...	...	...	...	...
...	...	...	...	...	...
...	...	...	...	...	...
...	...	...	...	...	...

INFORMATION TO FIND THE TREES IN POINT CLOUDS						
TreeID	Azm-60°	Quadrant	X_sin	Y_cos	X	Y
P1_01	160	IV	Distance*(sin(Azm-60))	Distance*(cos(Azm-60))	1.10	-4.88
P2_01	29	I	-6.17	-6.96	6.17	6.96
P3_04	233	III	2.94	5.11	-2.94	-5.11
P4_01	178	IV	5.35	-2.92	5.35	-2.92
...	...	...	...	...	...	...
...	...	...	...	...	...	...
...	...	...	...	...	...	...
...	...	...	...	...	...	...

INFORMATION OF TREES FOUND IN POINT CLOUDS					
X_PC	Y_PC	Dist_PC	Height_PC (+1.3)	Quadrant_PC	Polydata
0.2	-6.3	6.2	20	IV	yes
6	7	9.6	26	I	yes
0.2	4.2	4.1	15.5	I	yes
-3	-7	7.6	21	III	yes
...	...	...	...	...	...
...	...	...	...	...	...
...	...	...	...	...	...
...	...	...	...	...	...

## Appendix 2. Sensitivity analysis filling form

### PLOT 1

3D model ID	Tree ID	P1_01			
	Tree Specie	<i>Mauritia Flexuosa</i>			
	PatchDiam2Min	0.02	0.04	0.05	0.06
	r0	0	1	3	2
	r1	...	...	...	...
	r2				
	r3				
	r4				
	r5				
	r6				
r7					
r8					
r9					
<b>Sum</b>	0	1	3	2	

	Tree_ID	P1_04			
	Tree Specie	<i>Mauritiella Armata</i>			
		0.02	0.04	0.05	0.06
		0	1	2	3
		...	...	...	...
	0	1	2	3	

### PLOT 2

3D model ID	Tree ID	P2_01			
	Tree Specie	<i>Mauritia Flexuosa</i>			
	PatchDiam2Min	0.02	0.04	0.05	0.06
	r0	0	1	3	2
	r1	...	...	...	...
	r2				
	r3				
	r4				
	r5				
	r6				
r7					
r8					
r9					
<b>Sum</b>	0	1	3	2	

	Tree ID	P2_03			
	Tree Specie	<i>Mauritiella Armata</i>			
		0.02	0.04	0.05	0.06
		0	1	2	3
		...	...	...	...
	0	1	2	3	

### Appendix 3. Sensitivity analysis results

<b>Plot</b>	<b>Tree_ID</b>	<b>Specie</b>	<b>Best_PatchDiam2Min</b>
1	P1_01	<i>Mauritia flexuosa</i>	0.06
2	P2_04	<i>Mauritiella armata</i>	0.06
3	P3_05	<i>Mauritia flexuosa</i>	0.05
4	P4_06	<i>Mauritiella armata</i>	0.02
...	...	...	...
...	...	...	...
...	...	...	...
...	...	...	...

## Appendix 4. Filling form for sensitivity analysis tests

<b>Test user name:</b>					
<b>Plot</b> 1					
<b>Tree_ID</b> P1_05					
<b>Tree Specie</b> Mauritia flexuosa					
<b>PatchDiam2Min</b> 0.02 0.04 0.05 0.06					
<b>3D model ID</b>	r1				
	r5				
	r7				
	r9				
<b>Plot</b> 2					
<b>Tree_ID</b> P2_04					
<b>Tree Specie</b> Mauritiella armata					
<b>PatchDiam2Min</b> 0.02 0.04 0.05 0.06					
<b>3D model ID</b>	r1				
	r5				
	r7				
	r9				
<b>Plot</b> 3					
<b>Tree_ID</b> P3_03					
<b>Tree Specie</b> Mauritia flexuosa					
<b>PatchDiam2Min</b> 0.02 0.04 0.05 0.06					
<b>3D model ID</b>	r1				
	r5				
	r7				
	r9				
<b>Plot</b> 4					
<b>Tree_ID</b> P4_09					
<b>Tree Specie</b> Mauritiella armata					
<b>PatchDiam2Min</b> 0.02 0.04 0.05 0.06					
<b>3D model ID</b>	r1				
	r5				
	r7				
	r9				

## Appendix 5. Output files of AGB from QSM and allometric equations

AGB\_QSM.csv

Field names	Description
<b>name</b>	unique name per tree obtained after joining treeID and best.dmin
<b>plot</b>	number of plot
<b>treeID</b>	ID for each tree
<b>Specie</b>	name of palm tree specie
<b>best.dmin</b>	best patchdiam2min after sensitivity analysis
<b>QSM.vol</b>	mean volume from the ten models per tree (cm <sup>3</sup> )
<b>AGB_perugov</b>	AGB obtained using QSM.vol * wood density from Peruvian government document (kg/m <sup>3</sup> )
<b>AGB_GWDD</b>	AGB obtained using QSM.vol * wood density from Global Wood Density Database (kg/m <sup>3</sup> )

AGB\_allometry.csv, allometry.mauritia.csv, allometry.mauritiella.csv

Field name	Description
<b>Plot</b>	number of plot
<b>TreeID</b>	ID for each tree
<b>Specie</b>	name of palm tree specie
<b>Field_TLength</b>	measurement of trunk length taken in field (m)
<b>TLS_TLength</b>	measurement of trunk length taken from the point clouds (m)
<b>AGB_Field</b>	estimated AGB using trunk length from field (kg/m <sup>3</sup> )
<b>AGB_TLS</b>	estimated AGB using trunk length from point cloud (kg/m <sup>3</sup> )

## Appendix 6. Filling form of TLS stem height estimate per palm tree

Plot	TreeID	Specie	Top_TLS	Bottom_TLS	TLS_Height
4	P4_07	Mauritia flexuosa	9.03	-1.03	9.03-(-1.03)=10.06
3	P3_06	Mauritia flexuosa	11.38	-1.04	12.42
3	P3_05	Mauritia flexuosa	13.21	-1.03	14.24
...	...	...	...	...	...
...	...	...	...	...	...
...	...	...	...	...	...
...	...	...	...	...	...

## Appendix 7. Field and TLS trunk heights per palm tree

Plot	Tree ID	Specie	Field THeight (m)	TLS THeight (m)
1	P1_01	Mauritia flexuosa	20.00	21.05
1	P1_04	Mauritiella armata	15.06	14.61
1	P1_05	Mauritia flexuosa	14.50	14.66
1	P1_06	Mauritiella armata	13.00	13.00
1	P1_07	Mauritiella armata	13.00	11.44
2	P2_01	Mauritia flexuosa	26.00	24.16
2	P2_03	Mauritiella armata	16.50	17.76
2	P2_04	Mauritiella armata	13.50	14.67
2	P2_05	Mauritiella armata	12.75	13.03
2	P2_07	Mauritiella armata	9.00	10.60
3	P3_01	Mauritia flexuosa	24.00	21.71
3	P3_03	Mauritia flexuosa	16.50	16.50
3	P3_04	Mauritia flexuosa	15.50	16.28
3	P3_05	Mauritia flexuosa	14.00	14.24
3	P3_06	Mauritia flexuosa	11.00	12.42
4	P4_01	Mauritia flexuosa	22.00	21.72
4	P4_02	Mauritia flexuosa	22.50	20.30
4	P4_04	Mauritia flexuosa	15.00	15.72
4	P4_07	Mauritia flexuosa	10.00	10.06
4	P4_09	Mauritiella armata	6.75	5.95