

Proposal for Master's Research Project 2022

Localised Calibration of Allometric Scaling Models Using UAV Photogrammetry and Terrestrial Laser Scanning Derived Point-Clouds

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Abstract

The research proposal aims to produce accurate measurements of tree volume obtained from a combination of UAV photogrammetry derived point-clouds, and TLS obtained point clouds. From these measurements, total above ground biomass, and above ground carbon can be calculated. In conjunction with the UAV-TLS surveys, manual measurements of tree height and trunk diameter will be collected and used to estimate above ground biomass (and carbon) using traditional Allometric Scaling Models. The two estimations of above ground biomass will be directly compared, with a view to establish a procedure to calibrate allometric scaling model coefficients from UAV-TLS derived measurements, thus improving the local accuracies of ASM outputs.

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GLOSSARY OF ABBREVIATIONS

AGB – Above Ground Biomass

AGC – Above Ground Carbon

ALS – Aerial Laser Scanning

ASE – Allometric Scaling Equation

ASM – Allometric Scaling Model

BEF – Biomass Expansion Factor

CCC – Concordance Correlation Coefficient

CHM – Canopy Height Model

CV RMSE – Coefficient of Variation in Root Mean Square Error

DBH – Diameter at Breast Height (measured 1.3m from ground level)

EO – Earth Observation

GHG – Green House Gases

GPS – Global Positioning System

LIDAR – Light Detection and Ranging

QSM – Quantitative Structure Model

REDD - Reduce Emissions from Deforestation and Forest Degradation

RTK – Real-time Kinematic Processing

TLS – Terrestrial Laser scanning

UAV – Unmanned Aerial Vehicle

VEF – Vegetation Expansion Factor

1 INTRODUCTION

Accurate measurement of forest metrics is important for many reasons, but one specific requirement for reliable estimation and predictability of forest biomass comes from carbon offsetting mechanisms (Gifford, 2020; He et al., 2021). Afforestation or REDD+ carbon offset schemes rely on the accurate measurement of carbon sequestration in order to produce marketable carbon offsets which can be used to mitigate real world GHG emissions. As the world moves closer to 2050 net zero targets globally pledged to in the Paris agreement, the demand for carbon offsets is expected to increase exponentially compared to current levels (Trove Research, 2021).

1.1 CONTEXT OF THE RESEARCH

Significant overestimation of the above ground biomass (AGB) within REDD+ or afforestation offset projects could ultimately result in a net-increase of GHG emissions; as the carbon offsets that real-world GHG emissions have been mitigated against would not represent any real-world carbon sequestration (or retention in the case of REDD+ schemes) (Broekhoff et al., 2019). Conversely, a significant underestimation of AGB in such offset schemes can result in lost revenue for these projects (He et al, 2021) which could determine their financial viability and subsequent existence. Overall, accurate measurements of AGB that can be confidently used to evaluate carbon sequestration in offset projects are imperative to ensure this mechanism of carbon offsetting has environmental integrity, while simultaneously enabling project developers to make better informed assessments.

While Allometric Scaling Models (ASM) have been the dominant method for estimating forest biomass to varying degrees of accuracy, the advent and advancement of various remote sensing techniques has increased the ability of forest professionals to obtain measurements of better accuracy of forest characteristics than ASMs can provide (Lechner et al. 2020).

1.2 RESEARCH AIMS

This research proposes using two such remote sensing methods – UAV photogrammetry and Terrestrial Laser Scanning – to produce estimates for tree volumes and above ground biomass from which carbon content values can be derived. The research also seeks to propose a method to calibrate standard allometric scaling models with locally derived relationships between tree height, and trunk diameter (DBH).

1.3 RESEARCH OBJECTIVES

The specific objectives of the proposed research are as follows: -

- To use UAV obtained photographs to create a photogrammetric derived point cloud from which to obtain a Canopy Height Model.
- To obtain 3D point cloud reconstructions of individual trees from Terrestrial Laser Scanning equipment.

- To combine both UAV derived point cloud with TLS obtained point cloud and estimate total above ground biomass from the 3D model.
- To collect manual, ground-based measurements of tree height and trunk diameter to calculate an estimation of AGB from Allometric Scaling Models.
- To directly compare the estimations of AGB produced by both the UAV-TLS point cloud, and the traditional ASM.

2 LITERATURE REVIEW

2.1 ALLOMETRIC SCALING MODELS

Various Allometric Scaling Models (ASM) have been developed and used extensively by numerous parties to infer the total tree biomass contained within forests across the globe. Constructed from reference data obtained from the destructive harvesting of individual trees, ASMs attempt to relate tree characteristics such as tree height and trunk diameter at breast height (DBH, at 1.3m from ground level) with the total above ground biomass (AGB) of the tree. Albeit useful in obtaining an estimation of a forests AGB, they are limited in their ability to confidently predict an accurate value that can be easily verified. Thorough validation of ASMs involve extensive destructive testing of harvested trees, then diligently classifying, measuring and weighing the respective components of each tree to produce an adequate data set from which to construct an ASM. Although it has been shown that ASMs constructed from larger datasets obtained from a higher number of individual trees from a range of locations can provide good estimations of AGB (Fayolle et al., 2013; Chave, J. et al., 2005), other investigations have proposed using localised datasets to construct ASMs on smaller scales as they typically perform better (Kenzo et al., 2009; Basuki et al., 2009; Lima et al., 2012; van Breugel et al., 2011).

Chave et al. (2014) performed one of the largest studies and analyses of harvested trees, obtaining measurements taken from over 4000 harvested trees with a trunk diameter $\geq 5\text{cm}$ at 58 locations. Although they found that measurements of tree height, trunk diameter (DBH) and wood density could provide a reasonable prediction of the above ground biomass (AGB) of trees in pan tropical climates, the AGB of smaller trees that were less than 10 kg were significantly overestimated ($\leq +80\%$) and the AGB of larger trees greater than 8000 kg were typically underestimated ($\leq -20\%$).

A particular problem with Allometric Scaling Models is that the destructive tests from which the data sets used to create the models are obtained, are predominantly from smaller, more accessible trees and typically lack sufficient numbers of larger trees (Disney, M. et al., 2019). From the 4004-tree study that Chave et al. (2014) conducted, only around 10% had a height greater than 30m and a DBH greater than 70cm. The low number of destructive measurements from large tree samples which can be input into a Allometric Scaling Model results in a lower level of confidence in the AGB estimations of larger trees. Further compounding the problems with uncertainty surrounding the AGB estimations of large trees is the logistical difficulty of accurately measuring the height of larger, taller trees using

conventional ground-based measurement techniques; this is particularly true in dense, closed-canopy forests (Larjavaara et al., 2013; Hunter et al., 2013).

Demol et al. (2021) demonstrated that for temperate forests, while the AGB for conifer species was consistently underestimated by between -26.4% and -16.5%, AGB in broadleaf species were generally significantly overestimated by ASMs. Their results showed that the ASM for Common Ash (*Fraxinus excelsior*) for instance, overestimated the AGB by 71% compared to the respective destructively measured reference values.

Chave et al. (2014) found that the relationship between a tree's height and diameter varied depending on three Bioclimatic Stress Variables: *Seasonality Temperature*, *Precipitation Seasonality* and *Maximum Climatological Water Deficit*. This variance in the DBH-Height relationship poses further issues for the standardised Allometric Scaling Equations (ASE) used in ASMs as they operate under an assumption that such relationships are consistent across regions and climates, especially true for ASMs that utilise only DBH as an independent variable (Chave et al., 2014; Ledo et al., 2016). Chave et al. (2014) recommends deriving a localised relationship between DBH and Height and integrating that into any ASM being employed for a particular locality.

Variations in regional wood density are another significant factor that need to be evaluated for the purpose of accurately estimating AGB. Chave et al. recognised this in their work, and in a separate study produced by Baptiste et al. (2020) it was found that there can be significant variations in wood density across locations with differing altitudes, elevations and soil and climatic conditions.

2.2 EARTH OBSERVATION DERIVED ESTIMATIONS OF ABOVE GROUND BIOMASS

Remote sensing has enabled the measurement and monitoring of a range of environmental parameters that had been either incredibly difficult, or impossible to obtain previously. Obtaining data from satellite instruments does also have its limitations, Optical observations are sensitive to cloud cover, season and solar zenith angle – in addition to the inability to penetrate through the canopy and capture the structure below. Satellite radar and light detection and ranging (LIDAR) measurements are limited in their ability to penetrate dense vegetation and are also unable to fully capture the full forest structure (Urbazaev et al., 2017).

Earth Observation (EO) data obtained from combining satellite measurements from LIDAR, radar and optical sensors has previously been used to provide estimations of AGB on a regional scale, but results can produce errors of over 100% (overestimation) when compared to reference values (Zolkos et al., 2013; Jucker et al., 2018). Another fundamental limitation of using EO data is the resolution which can be achieved. Low resolution datasets of forest characteristics result in an inherently large systematic error which can render them unsuitable for certain applications (Zolkos et al., 2013). The level of uncertainty associated with EO derived AGB estimations of forests is problematic when determining carbon sequestration rates in offset projects for reasons previously discussed.

2.3 AIRBORNE LIDAR DERIVED AGB

LIDAR instrumentation mounted onto aeroplanes, helicopters or unmanned aerial vehicles (UAVs) is also regularly deployed to measure forest characteristics. Although airborne LIDAR is not able to capture as large of an area in the same amount of time as satellite data can, it can capture sufficiently large areas and at a higher resolution and better accuracy than satellite sensors can yield (Urbazaev et al., 2017; Jucker et al., 2018). A similar issue exists with airborne lidar scanning (ALS) as with satellite lidar; ALS LIDAR is unable to penetrate through dense vegetation, so is unable to accurately capture forest structure from the crown all the way to the forest floor (Jung et al., 2010). Scattering of the laser pulses amongst the leaves and branches of the upper canopy results in considerable ‘noise’ and the erroneous points registered by the LIDAR return sensor leads to inaccuracies in the final measurements (Korpela et al., 2012; Lee et al. 2018). ALS is effective at providing measurements that can be used to create canopy height models (CHM). By measuring the heights of individual trees, a CHM can be created from which the mean height, range of heights, and number of trees can be derived (Jucker et al., 2018; Hao et al., 2019). ALS augmented ASMs have shown to provide better accuracy in estimating AGB than ASMs constructed from traditional ground-based measurements of DBH and/or height (Zhao et al., 2012).

2.4 UAV PHOTOGRAMMETRY

Unmanned Aerial Vehicles have in recent years become increasingly advanced and utilised in forestry management (Dainelli et al., 2021). Although LIDAR instrumentation for UAVs is available, the high cost of all the necessary equipment can be prohibitive. Alternatively, photogrammetry – which involves the amalgamation of overlapping images taken from different positions and angles – can generate 3D terrain models from which measurements can also be derived. Modelling and measurement of stand-alone individual trees from photogrammetry has demonstrated good accuracies in measurements of branch diameter and branch length, with R^2 values of 0.87 and 0.98 respectively (Lane Scher et al., 2019). Accurate, larger scale modelling of forest plots that have been derived from photogrammetry have proved more difficult to create accurately, with the inability to photograph through the canopy a fundamental limitation (Kameyama et al, 2020). UAV photogrammetry can produce canopy height models to a good which can be used to either calibrate ASM parameters, or compliment TLS data sets accuracy (Torres-Sánchez et al., 2018).

2.5 TERRESTRIAL LASER SCANNING (TLS)

TLS operates using LIDAR instrumentation where the sensor is located at ground-level (typically on a tripod). Although the range which can be captured is considerably smaller than satellite or aerial LIDAR, TLS can capture the under-canopy structure of forests better than the aerial techniques (Paris et al., 2017). TLS devices which are smaller and portable, provide an element of versatility to forest surveys and can be less logistically complex to conduct than ALS surveys.

TLS had first been used initially in forest inventory surveys to record rudimentary measurements of tree count, tree spacing trunk diameters and tree height. These pioneer

studies with TLS devices showed good accuracy but highlighted limitations (Yao et al., 2011; Strahler et al., 2008; Calders, K. et al., 2018; Hopkinson et al., 2004). TLS works on a line-of-sight principle, so the range over which measurements can be obtained within a forest is limited by: - 1) the specifications of the device used (Abegg et al., 2021), and 2) the density and structure of the forest. As LIDAR pulse cannot penetrate through vegetation, high density forest conditions limit the number of trees and depth of forest that can be captured from a single position (Boucher et al., 2021). TLS is also limited in its ability to capture the tops of tree crowns as well as much of the upper canopy in closely packed forests. Consequently, TLS is not suitable as a stand-alone method for obtaining accurate measurements of tree heights (Wang et al., 2019).

Multiple scans from various positions can provide a solution to the limitations of range and line-of-sight obstruction, albeit at the cost of increased survey times and processing requirements (Disney, M. I. et al., 2018).

TLS derived 3D reconstructions of tree structure have been shown to yield high accuracies in AGB estimations when compared to destructively harvested reference values (combined $R^2 = 0.97$) (Tanago et al., 2018; Calders, et al., 2015). Careful design of forest TLS surveys can produce highly detailed 3D models of forest plots, with accurate reconstruction of individual tree structures. An example is the high-resolution reconstruction of 1 Ha plot of several forests (Fig. 2.1) produced by Calders et al. (2018) from which AGB measurements and other forest characteristics could be derived.

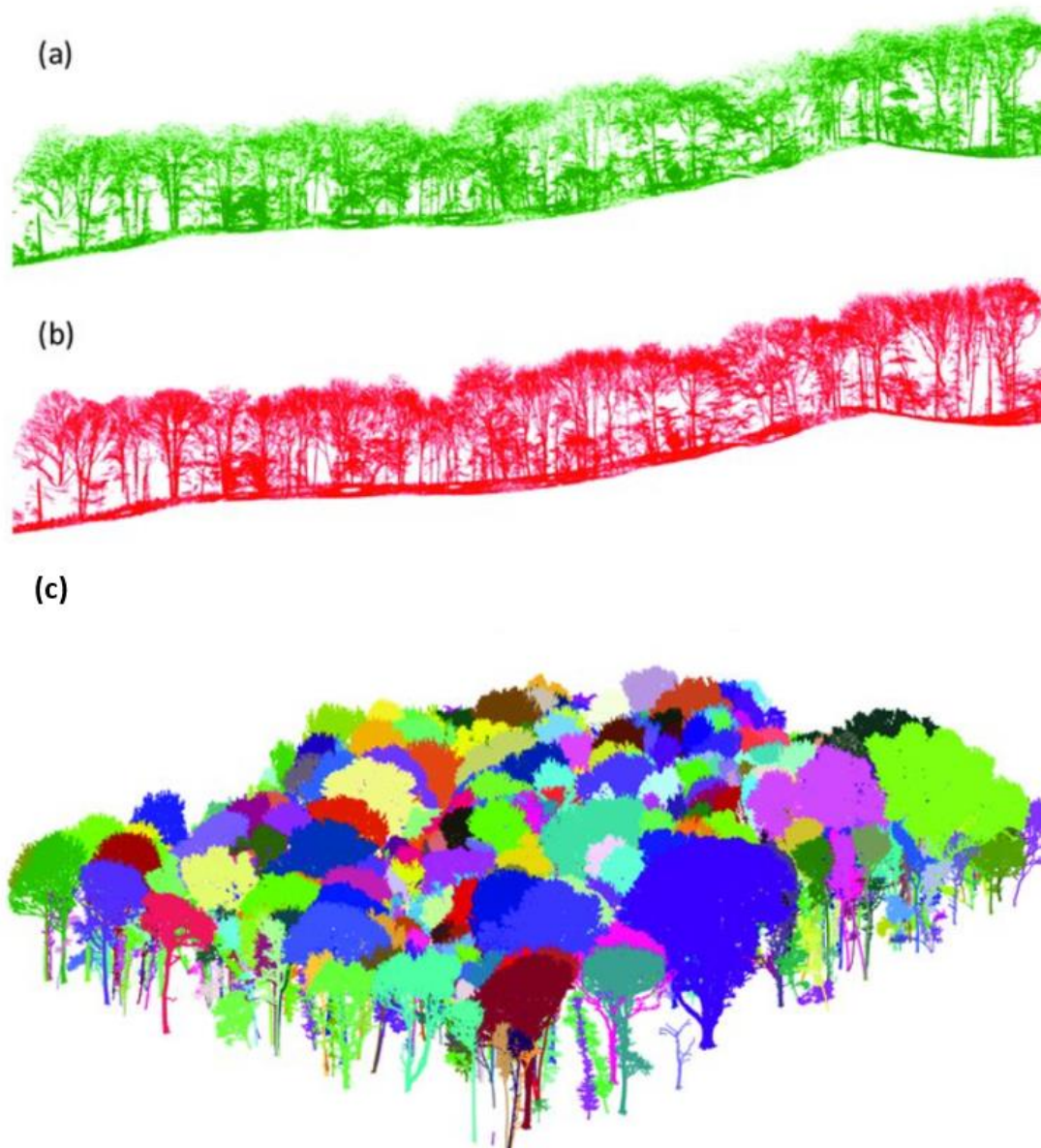


Figure 2.1 - Terrestrial laser scanning (TLS) data acquisition in Wytham Woods (a) TLS cross-section transect in leaf-on conditions; (b) TLS cross-section transect in leaf-off conditions and (c) Segmented one hectare point cloud of Wytham Woods (Calders et al. 2018)

2.6 VALIDATION OF TLS DERIVED MEASUREMENTS

There are few studies that have directly compared TLS derived AGB estimations against destructively harvested measurements (Disney et al., 2018). Two significant studies that directly compare TLS derived estimations of AGB with destructively obtained reference values are Tanago et al. (2018) and Calders et al. (2015).

Tanago et al. (2018) performed TLS measurements from 29 plots at sites in Peru, Indonesia and Guyana. From each plot, the largest tree was harvested and destructively tested. Measurements from nine of the harvested trees (three from each region) was used to

perform a sensitivity analysis of the modelling procedure. The remaining 20 trees were used to compare the TLS derived measurements to the reference values and determine the accuracy of the QSM. Tanago et al. used a QSM proposed by Raumonen et al. (2014) Their results showed that total tree volume was predicted with a CV RMSE of 23.7% compared to reference values, and AGB was predicted with a CV RMSE of 28.4% and a concordance correlation coefficient (CCC) of 0.95. The larger error in the AGB estimation can be attributed to an assumed value of wood density being used in the TLS derived measurements. The actual wood density of the harvested trees differed from this assumed value. Overall, they demonstrated that TLS derived measurements could provide a more accurate estimation of AGB compared to traditional pantropical ASM estimations – which in this study produced a CV RMSE of between 35.6%–54.95% and a CCC of between 0.89–0.73.

Calders et al. (2015) conducted a similar study that evaluated TLS derived measurements and traditional ASMs against harvested reference values obtained from 65 variants of Eucalyptus tree in Victoria, Australia. The TLS-QSM estimations of AGB resulted in a CCC of 0.95, and overall, overestimated AGB by 9.68%. Similarly to Tanago et al., the TLS estimations outperformed traditional ASMs, which underestimated AGB by between 29.85% and 36.57% (CCC between 0.68 – 0.78).

2.7 CONSTRUCTION OF POINT CLOUDS FROM TLS DERIVED

TLS measurements produce what are termed *point-clouds*, where each individual point represents a discrete spatial location with a defined X, Y and Z co-ordinate relative to the sensor. TLS instruments can record millions of discrete *points* from a single scan from which a 3D representation of the surveyed object can be constructed to a high degree of accuracy – but only within a relatively small radius (Abegg et al., 2021; Boucher et al., 2021). From these generated point clouds, highly detailed and accurate 3D models of trees can be re-constructed using Quantitative Structure Models (QSM) which combine multiple, co-registered TLS data sets.

2.8 QSM METHODOLOGY

The methods and techniques used to produce point clouds, and the subsequent quantitative structure models will ultimately determine the accuracy of the results that can be obtained from the model. Manual and computational processing requirements can be limitations that need to be balanced with the level of accuracy needed for the application. Demol et al. (2021) summarises several novel approaches to constructing QSMs from which useful measurements can be derived. Notably, Hackenberg et al. (2014) generated a QSM that reconstructed 99% of the tree with submillimetre accuracy when compared with the original point cloud data.

2.8.1 TreeQSM

The QSM procedure validated in the Tanago et al. (2018) study as having a high degree of accuracy was the TreeQSM procedure developed by Raumonen et al. (2014). Their QSM utilises a process of *least-squares cylinder fitting*; Noise and extraneous data is first removed from the point cloud, then the separate vegetation components within in the cloud are

categorised and stratified. As shown in figure 2.2 - small cylinders are progressively fitted along the point cloud structure in line with a majority of points¹.

Lau et al. (2018) compares TreeQSM results against harvested reference in their study; they found that TreeQSM was proficient at accurately modelling 95% of branches greater than 30cm which overall, led to a successful reconstruction of 97% of tree volume. Though they identify the procedures inability to accurately recognise and model finer branches of smaller diameters ($\leq 20\text{cm}$).

Hackenberg et al. (2015) had previously identified inaccuracies in small branch reconstruction using TreeQSM procedure, finding that branches smaller than 4cm were significantly overestimated. They reduced this error from 33.84% to 3.56% by applying *biomass expansion factors* (BEF) to the finer branch structures.

Demol et al. (2021) deploy a similar strategy that adjusts QSMs from TLS derived point clouds with vegetation expansion factors (VEF). Comparing TLS derived data sets to 65 harvested reference trees from 4 tree species in Belgium, initial QSMs produced an overall overestimation of volume of +21%, which were reduced to -12% and +9% when two respective VEFs were applied. Of note, were the initial overestimations in volumes for Common Ash (*Fraxinus excelsior*), which was +35.3%, and Common Beech (*Fagus sylvatica*) which was +19.8%. These errors were reduced to -6.7% and +2.2% respectively, which performed better than the ASM which produced errors of -10.9% and +4.2%.

Both the Hackenberg and Demol studies demonstrate that inaccuracies in the capture and modelling of finer branch structures could be mitigated by the application of expansion factors.

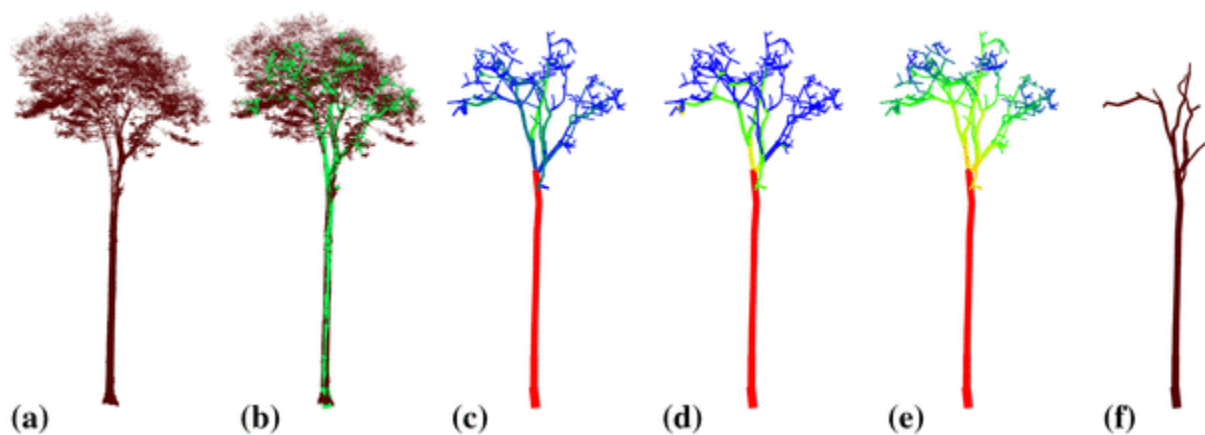


Figure 2.2 - (a) Tree point cloud, (b) TreeQSM reconstructed from the tree point cloud. (c) QSM branches classified by length (d) by branch diameter and (e) by branching order. (f) QSM branches which were paired with manually measured branches (Lau et al. 2018)

¹ Two short videos outlining the TreeQSM process can be found here: <https://www.youtube.com/watch?v=wANRdliE1zQ&t=4s> and here: <https://www.youtube.com/watch?v=i0Emjwp-fmU>

3 PROPOSED METHODOLOGY

3.1 LOCATION

A location to undertake the study has been identified as the Gower Gold Club in Three Crosses, Swansea. The golf course has several small plots of woodlands on its periphery which are suitable to obtain the various measurements from. The landowner has provided written consent which is provided in appendix 5.1.

3.2 EQUIPMENT

The university has the following items of equipment that can be utilised for the research:

- Leica BLK360 Terrestrial LIDAR Scanner –
- DJI Phantom 4 pro V2.0 UAV
- DJI Phantom 4 Multispectral RTK
- DJI GPS Ground Station

The Leica 360 will be used to generate the TLS point-cloud. The DJI Phantom 4 multispectral RTK will be used in conjunction with the GPS ground station to produce a CHM with high accuracy.

3.3 MEASUREMENT AND DATA COLLECTION

The proposed methodology for this research is to primarily combine 1) Canopy height models generated from UAV photogrammetry derived point clouds with 2) under-canopy point-clouds obtained from TLS measurements of individual trees taken from multiple positions. Robust co-registration of these two point-cloud data that enable accurate reconstruction and derivation of tree and forest metrics has been demonstrated in previous work (Holopainen et al., 2014; Dobre et al., 2021). The research aspires to obtain the following measurements.

From the UAV photogrammetry derived point-clouds: -

- 1) Derive a Canopy Height Model, from which the following can be obtained;
 - a) Total number of trees within the defined plot area.
 - b) Minimum and maximum tree height values (range).
 - c) Mean tree height of the defined plot.
 - d) The distribution of individual trees within defined intervals of height range.
 - e) Height measurements of selected individual trees.
- 2) The following measurements from the TLS derived Point Clouds;
 - a) The DBH of selected trees
 - b) Heights of selected trees
 - c) The total volume of the selected individual tree (TLS point cloud only)

Measurements from manual, ground surveys will also be obtained to enable validation of some of the point-cloud values derived from the analysis process;

- 3) a) A count of the total number of trees in the defined plot area.
- b) the DBH of selected trees.
- c) Heights of selected trees obtained from traditional instruments (using either a Rangefinder, Hypsometer, Clinometer or measuring rods)

3.4 ANALYSIS OF DATA

From the initial UAV derived CHM, several individual trees will be selected (1e). This selection will represent different tree heights at regular intervals across the range of heights measured (1b). The distribution of tree heights (1d) will be evaluated to determine whether the number of samples from specific height range intervals should be increased – to produce a weighted sampling set.

Selected samples will then be individually surveyed from multiple scan positions with TLS to produce a detailed 360° 3D point cloud of the tree. The UAV derived point clouds of the upper portions of the tree will be integrated with the TLS point-cloud to produce a complete 3D construction of the individual sample trees. Each 3D construction will be processed using the TreeQSM procedure, from which measurements of DBH (2a), Height (2b) and Total Volume (2c) will be obtained.

3.5 PROPOSED DATA COMPARISONS

From the processed data, direct comparisons of the following measurements can be made:

- Height measurements of selected trees obtained from UAV CHM, TLS and manual ground measurements - Operating on the assumption that the UAV derived canopy heights (1e) will provide the most accurate measurements, TLS (pre-integration with UAV point cloud) (2b) and manually obtained heights (3c) will be compared against the UAV derived values.
- DBH measurements obtained from TLS and manual measurements – Manual measurements (3a) are assumed to be more accurate than TLS derived DBH (2a), so TLS compared against these values.
- The total number of trees within the defined plot identified by UAV and manual measurements (minimum DBH and heights will need to be defined) – the UAV derived tree count (1a) will be compared against meticulous manual tree count (3a); with manual assumed to be more accurate.
- Using the combined TLS-UAV point cloud and subsequent QSM outputs for tree volume as the reference:
 - a) compare against the TLS-only point cloud and QSM volume estimations.
 - b) compare against ASM generated values of tree volume using the following inputs:
 - i. Manually obtained measurements of Height and DBH
 - ii. TLS derived values of both Height and DBH
 - iii. UAV derived values of Height, and TLS derived values of diameter
 - iv. UAV derived values of Height, and manual measurements of DBH

3.6 RESEARCH STEPS AND PROCESS

Figure 3.1 Below summarises the proposed research steps.

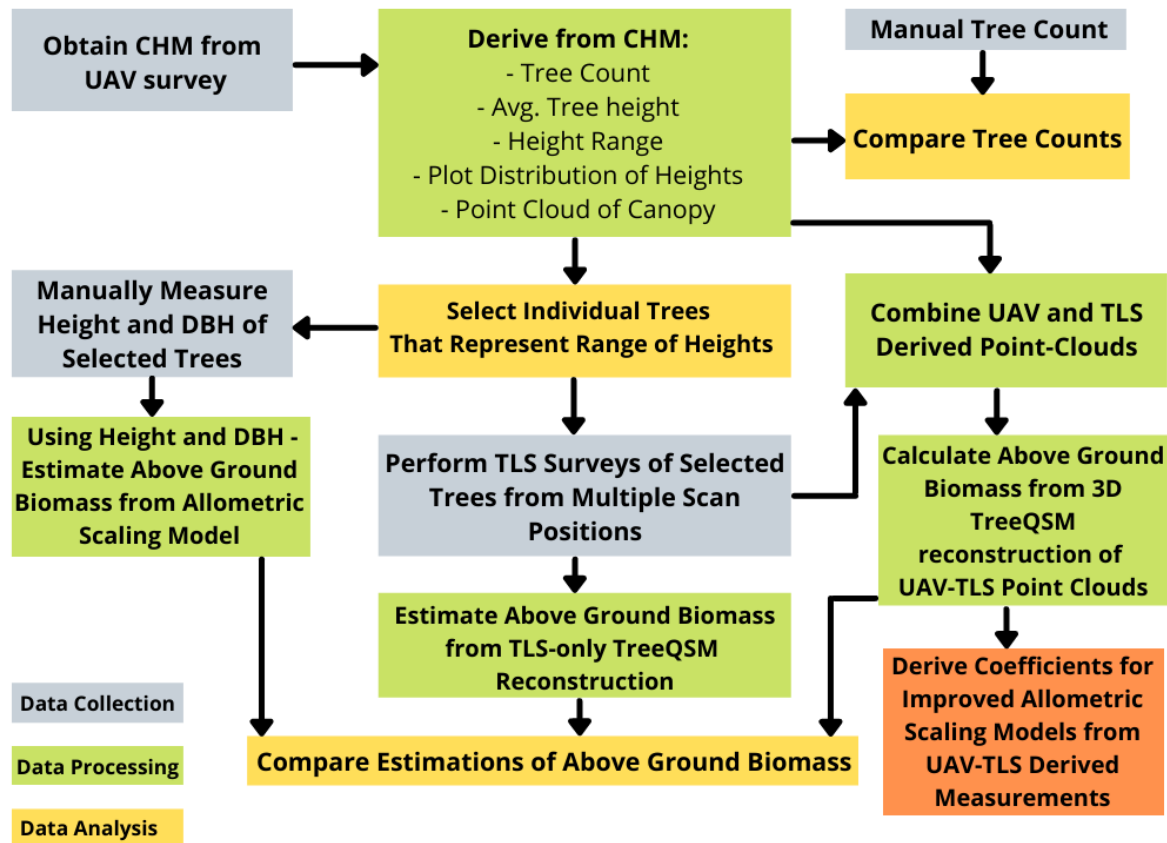


Figure 3.1 - Flowchart of Research Steps

4 OUTCOMES AND APPLICATIONS OF RESEARCH

4.1 OUTCOMES - EVALUATION OF FINAL RESULTS

The research principally aims to identify differences in AGB values obtained from UAV-TLS measurements and ASM predictions. Evaluations of the specified comparisons made between the different methodologies will be discussed. Any deviations identified from the TLS-UAV derived AGB values, and the AGB estimations obtained from 1) the four ASM outputs (i. – iv.), and 2) the TLS-only derived AGB will be quantified, and potential root error causes explored. Time and labour intensity of the respective techniques will be captured and factored into the final analysis, as it is expected that there will be a trade-off between convenience and accuracy.

4.2 APPLICATIONS OF RESULTS

This study will endeavour to recommend a procedure to locally calibrate species-specific ASMs which will reliably provide superior accuracy to traditional ASM measurement techniques. As has been demonstrated in previous work, measured relationships between tree height and DBH against total tree volume derived from UAV-TLS can be used to produce local Allometric Scaling coefficients that can be extrapolated over larger plot areas and be used to infer overall AGB and AGC (Fischer et al., 2019; Stovall et al., 2018; Burt et al., 2020).

4.3 POTENTIAL SOURCES OF ERROR

For both UAV and TLS surveys, potential error can arise from a number of sources, examples are - non-ideal weather conditions like rain and wind (Demol et al., 2021), inaccurate co-registration of individual TLS scans and UAV photographs, and even device specifications (Calders, et al., 2020; Abegg et al., 2021). Sources of error incurred during the course of the research will need to be identified and assessed in the final evaluation. Estimations of Above Ground Carbon will depend on the values of wood density used, the research will likely use values from reference tables. Baptiste et al. (2020) identified notable wood density variations between individual trees of the same species in differing locations within temperate regions, one example this being several varieties of oak (*Quercus pubescens*, *Quercus petraea* and *Quercus robur*), which were found to have a standard deviation in wood density of approximately 10%. Deviations in wood density is a source of uncertainty that could also be explored in this research, by extracting and analysing samples of wood from the selected trees to obtain density values.

4.4 PROPOSED ALTERNATIVE/ADDITIONAL MEASUREMENTS AND EVALUATIONS

Some other aspects relevant to the research could potentially be explored as alternatives to the current proposal, or in addition to it – time allowing.

- Obtaining sampling of wood density from the selected trees (core drilled samples)
- Explore augmenting the QSM's with Biomass/vegetation expansion factors.
- Using the UAV derived CHM and manually measured DBHs – establish localised height-DBH relationship for improving local ASMs (recommended by Chave et al. 2014)

5 CONCLUSION

The overarching ambition of the research is to establish a protocol which will allow the calibration of Allometric Scaling Models from localised, non-destructively obtained estimations of the above ground biomass of a forest plot using a combination of UAV and TLS derived measurements. This protocol could then be utilised as a convenient and reliable method to determine carbon sequestration in carbon offsetting projects.

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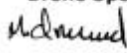
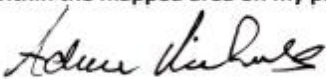
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7 APPENDICES

7.1 LANDOWNER PERMISSION FORM

Drone Flight - Landowner Permission Form		 Prifysgol Cymru Y Drindod Dewi Sant University of Wales Trinity Saint David
Location Details		
Landowners Name	Adrian Richards	
Address of Location (if applicable)	Gower Golf Club, Cefn Goleu Three Crosses Swansea SA4 3HS	
Date(s) and Time(s) of Flight(s)	1st Flight 25/03/22 12.00 - 18.00	
Map of Flight Location		
 Gower Golf Course Cefn Goleu, Three Crosses, Swansea, SA4 3HS Lat: 51.6376861 Long: -4.0632553		
Name of Drone Operator(s) Matthew Drummond Mohammed Shorab		Drone Operators Signatures:  
I, the named landowner grant permission for the named drone operator(s) to conduct drone flights within the mapped area on my property.		
Landowner Signature: 		Date: 24-3-22