PROSIECT CARTREFI O BREN LLEOL
THE HOME-GROWN HOMES PROJECT

Estimating Timber Value and Carbon in Complex Woodlands Using Terrestrial Laser Scanning

Heddwyn Bye, Woodknowledge Wales

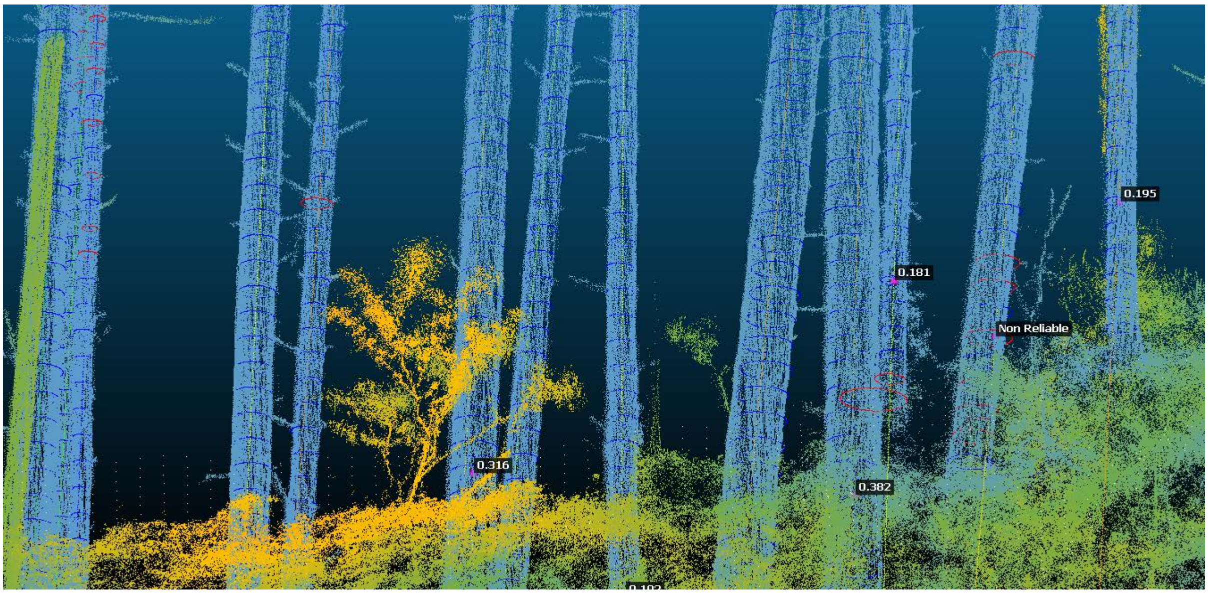

Figure 1: LiDAR point cloud of forest showing fitted diameter sections & stem diameters (labels) processed using the 3DFin plugin.

Executive Summary

Timber used in long-lifespan harvested wood products (HWPs) plays a crucial role in carbon storage. However, in the UK, the majority of hardwood timber is used for firewood, with only a small proportion used for high-value long-lifespan applications. Similarly, the coarse grading criteria for softwoods limit the targeted utilisation of timber products. The application of ground-based LiDAR instruments to the measuring of trees and forests presents an alternative to manual tree measurement using conventional forest inventory instruments.

The application of terrestrial laser scanning (TLS) to trees enables the time-efficient and precise measurement of forest inventory metrics including tree diameter at breast height (DBH), height and location. In addition to these traditional measurements, TLS can also be used to capture data on tree stem form - stem sweep, taper, lean and

branch incidence – from which timber properties can be estimated. Furthermore, the measuring of whole trees using TLS can be used to more accurately measure the carbon content of standing trees.

More accurate timber assessments could increase the proportion of wood used in high-value applications, reducing waste and enhancing carbon storage in the built environment. Improved surveying methods would also support better management of underutilised woodlands, contributing to economic and environmental sustainability while aiding net-zero emissions goals.

An ongoing research study at Bangor University investigated the potential for the application of TLS measurements to predict the potential timber product value and carbon content of trees in a range of woodlands in Wales. Eight woodlands were studied, varying in structural complexity and management history, representing a wide range of woodland conditions from uniform coniferous plantations to unmanaged naturally regenerated woodland. The project compared TLS-derived measurements of tree DBH, height, sweep, taper and lean to their manually measured counterparts obtained using conventional forest mensuration instruments. Reflecting the results of previous studies, high levels of correlation were found between TLS and manually measured metrics. A sawlog selection algorithm was then devised to enable the estimation of timber product output from the scanned trees. This was found to be effective in predicting the timber product output and therefore potential timber value of standing trees, as well as the carbon content of sawlog products.

Though effective in measuring timber value and carbon content of trees, this project identified several limitations to the use of TLS in measuring complex forests. Firstly, TLS instruments are sensitive to adverse weather conditions and cannot be used in rain or when wind speeds are greater than 15 mph. Secondly, the processing of TLS data is complex, requiring specific training and expertise. In order to be taken up in real-world forestry applications, an automated data processing platform must be developed. Finally, the current cost of TLS surveying is higher than that of conventional forest inventories, limiting its uptake.

Key Points

- LiDAR technology enables precise measurement of objects, including trees.
- When applied in forestry, LiDAR can accurately measure key inventory metrics such as diameter at breast height (DBH) and tree height.
- Beyond basic measurements, LiDAR captures stem form details, helping to assess timber quality and variation in wood properties.
- These data allow for estimating the volume of sawlog-quality timber in standing trees, aiding in valuation before harvest.
- Measuring tree volume with LiDAR also improves estimates of carbon stock in standing forests.
- Further development is required to use this in real-world forest inventory applications.

Introduction

This report summarises the progress of an ongoing Master's by Research (MScRes) project at Bangor University investigating the potential of terrestrial laser scanning (TLS) to estimate the timber value and carbon content of standing trees in a range of woodlands across Wales. The application of this technology is particularly relevant for small, marginal woodlands, where conventional measurement methods make it difficult to assess tree form and size accurately. The term 'complex woodlands' is hereafter used to refer to such woodlands, which are often naturally occurring or semi-natural and occur in small-to-medium sized plots throughout the UK.

LiDAR (Light Detection And Ranging) technology has been used to measure tree biomass, stem form variation, and potential sawlog outputs in various woodland types. It has not, however, yet been applied to complex UK woodlands. Additionally, no studies have tested its use against UK-specific sawlog grading criteria—a critical step in integrating this technology into practical forestry operations.

This study was aimed to test the ability of TLS measurements to measure variation predict the operational timber output from standing trees in woodlands of varying structural complexity. The ability of TLS instruments to measure variation in the stem form of trees was assessed in eight woodland sites, before using this data to predict the potential timber products harvestable from a tree. From this data a potential value for each tree and therefore each surveyed plot was calculated using publicly available timber sales data from 2023. Data on tree and sawlog dimensions were also used to calculate the tree carbon content from LiDAR measurements.

Background Information

Timber Properties and Use

Timber used in long-lifespan harvested wood products (HWPs)- such as furniture and construction materials retains sequestered carbon for a longer time period than short-lived applications such as paper or firewood. Maximising the proportion of timber used in high-value products is therefore critical for carbon storage. Despite the widespread availability of broadleaf timber from UK woodlands, only 4% of the hardwood timber harvested in the UK is used for structural applications, with the majority used as wood-fuel [1]. Increasing the use of both hardwood and softwood timber from UK woodlands therefore presents an opportunity to enhance carbon storage within the built environment.

The structural properties of timber are closely linked to tree form. Knots indicate underlying defects, while greater sweep (sagitta) reduces bending and compression strength. Leaning stems produce reaction wood, compromising timber quality. Accurately measuring these characteristics is essential for assessing potential timber value.

Conventional Timber Valuation Methods

Current methods of valuing standing timber are limited due to the difficulty manually measuring variation in the form of standing trees. Due to the difficulty manually measuring sweep, taper or lean, assessments are generally made using visual field assessments of standing trees. In the UK, log grading relies on the manual visual assessment of these key properties. In this was sawlogs are broadly classified into two categories: green sawlogs (higher quality) and red sawlogs (lower quality). Green sawlogs must meet strict criteria, with minimal taper, sweep, lean, and branch incidence. Red sawlogs, by contrast, may exceed these thresholds and are subject to less stringent grading standards.

LiDAR based measurements present an opportunity to precisely measure variation in stem form metrics, improving the precision of timber valuation. Improved timber valuation techniques would be highly useful in the estimation of the timber value of complex woodlands such as those on farms and other small-to-medium privately owned woodlands. Many such woodlands often receive little management due to the difficulty measuring their value using conventional instruments. A key benefit of improved surveying is that a higher proportion of harvested timber could be classified as high-value wood products, rather than being downgraded to firewood or biomass. This extends the lifetime of harvested wood, keeping its sequestered carbon locked up longer and contributing to net-zero emissions goals. Furthermore, the ability to more accurately measure tree volume and therefore carbon content is particularly useful in enabling the assessment of the carbon stored in such woodlands.

LiDAR Instruments

The development of LiDAR technology has transformed how we measure trees and forests, offering a powerful tool for assessing tree form and estimating factors that influence the value of standing trees [2,3]. LiDAR works by emitting rapid laser pulses—up to one million per second—and measuring the time it takes for each pulse to reflect off objects and return to the scanner. This process allows LiDAR to create highly accurate, three-dimensional (3D) maps of the environment by reconstructing a 'point cloud'—a collection of millions or even billions of points that precisely capture the structure of the scanned area. Since their introduction in the early 2000s, terrestrial laser scanners (TLS)—a type of tripod-mounted LiDAR device—have become valuable tools for forest surveys [4]. Unlike traditional measurement methods, which rely on manual tools and broad estimations, TLS can capture highly detailed 3D scans of trees. This allows for precise measurements of tree volume, stem straightness (sweep), taper (how the trunk narrows toward the top), and lean [3–5]. These detailed measurements support a wide range of forestry applications, including estimating timber value, monitoring forest growth, mapping forest compartments, and calculating aboveground biomass (AGB) for carbon stock assessments [6].

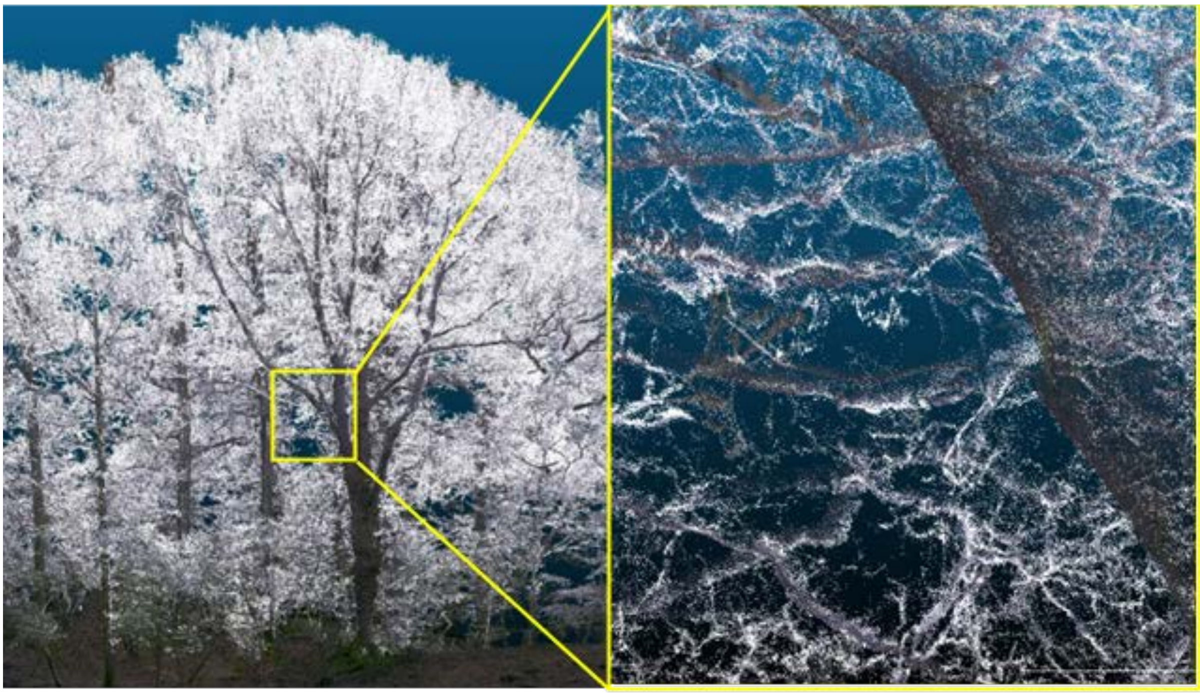

Figure 2. TLS point cloud of a stand of oak trees, colourised.
Left: the whole point cloud is shown. **Inset Panel**: a zoomed-in section in which the individual points making up the model of the tree can be seen. Processing these point clouds enables measurement of objects within them, and subsequently, the measurement of variables of interest for forest inventory applications.

LiDAR Measurements

A key advantage of TLS over traditional methods is its ability to improve the accuracy of measurement of tree form in addition to the capturing of conventional forest inventory metrics (DBH and height). In addition to this, tree aboveground biomass and therefore carbon content can be measured more accurately than using manual measurement methods. Conventional approaches rely on allometric equations - mathematical formulas that estimate one aspect of a tree's structure from another, such as using diameter at breast height (DBH) to predict total volume. While these equations are efficient and require only basic tools, they are based on generalisations drawn from field data rather than direct measurement of individual trees. As a result, they may not fully capture the irregular structure of broadleaf trees or account for the contribution of smaller branches. In one study, tree volume estimates derived from allometric equations were found to be roughly half of those obtained using TLS, highlighting the potential of laser scanning to provide more precise assessments of the biomass and therefore carbon content of trees in woodlands [7].

The measurements enabled by LiDAR instruments therefore include the following:

- **Forest inventory metrics** – DBH, height, tree positions, biomass, and stand-level measurements [3,9]. By improving the efficiency of these measurements automated LiDAR-based forest inventories could improve the resolution of carbon assessments and improve the efficiency of forest inventories.

- **Tree structure and form** – Stem shape, lean, and taper [4,8]. Variation in these factors significantly affects timber properties.
- **Stem defects** – variation in which affects product yield and wood fibre characteristics [10–12]. By measuring stem defects, greater resolution of timber product valuation can be achieved.
- **Pre-harvest timber estimation** – Predicting merchantable timber volume and value before felling [5,14].

LiDAR Data Processing

When a forest is scanned using LiDAR, the resulting point cloud consists of unclassified data, meaning individual objects like trees are not automatically identified. To extract useful information, the data must be processed to isolate trees and measure their dimensions. This step is essential for calculating key forest inventory variables, such as tree height, volume, and stem quality. However, processing LiDAR point clouds is complex and depends on the capability of the algorithms used. Currently, this process requires specialised training and significant manual effort, limiting the widespread use of TLS in forestry.

Developing automated processing methods is a key step in making TLS more accessible for operational use. Recent research has shown that real-time data processing is possible—Li et al. (2023) demonstrated an automated system that processed point cloud data from a helmet-mounted scanner in real time, providing instant forest inventory metrics [15]. However, such algorithms are not yet widely available, needing further testing and integration into user-friendly software to enable wider uptake of this technology if the benefits of its use are to be fully realised.

Methods and Results

Data Collection

This study selected eight distinct woodland sites across Wales for scanning using TLS. A 10m x 10m plot was selected from within each site. Eleven plots were scanned in total, with two plots measured at three sites and one surveyed at the remaining five sites. The sites ranged in structural complexity and management history from tall, well-managed, uniform plantations of Douglas fir (*Pseudotsuga menziesii*) to an unmanaged, dense, structurally complex farm woodland plot containing alder (*Alnus glutinosa*) and hazel (*Corylus avellana*). The remainder of the plots along this gradient represented intermediate levels of structural complexity. A total of 55 trees were surveyed, 32 of which were broadleaved and 23 coniferous.

Each plot was scanned using a Leica BLK360 TLS device using a multi-scan regime - four scans on each of the four plot corners - to capture data on all four sides of all the trees in the plot. This scanner records 360,000 points per second with a 3D point accuracy of 6mm at 10m from the scanner with a maximum range of 60m. Artificial reference spheres were placed in the plots to enable the co-registration (alignment) of individual scans (figure 3). In addition to TLS, one plot was scanned using a Leica BLK2GO - a handheld mobile laser scanning (MLS) device.

Figure 3. The Leica BLK360 device used to scan a plot (central) and two of the three reference spheres used to act as tie-points to assist in alignment of individual scans.

Each plot was also surveyed using conventional manual measurement instruments for comparison against the TLS measurements. The trees' DBH, total height, stem taper, sweep and lean were measured. Finally, a map was made of each plot using the ForestScanner application. This application utilises the close-range LiDAR scanner on an iPhone to map stem locations in a forest and is also able to measure stem DBH by fitting a circle to the stem point cloud. It was used here to obtain a stem map of the trees surveyed so that the field-measured trees could be matched with their TLS-measured counterparts.

LiDAR Data Processing Pipeline

Following the surveying of forest plots, a proprietary multi-platform data processing pipeline was devised to enable measurement of stem form metrics from tree point clouds. A simplified version of this methodology is shown in figure 4 below.

a

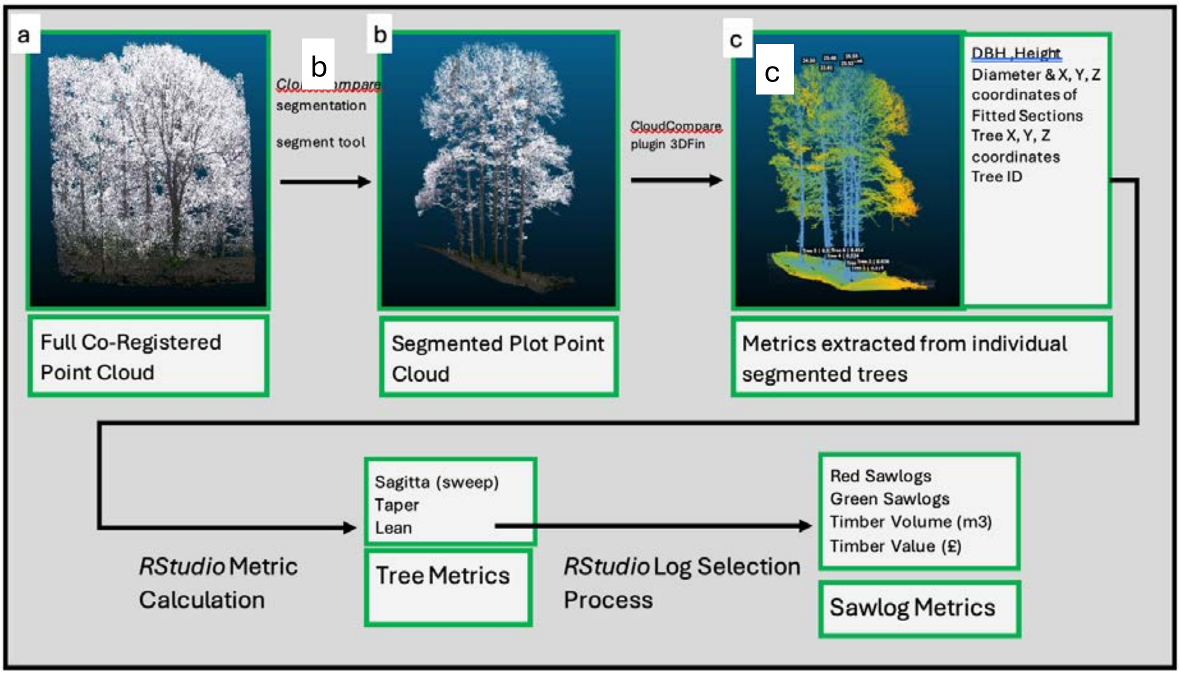

Figure 4. Method used for the calculation of metrics from LiDAR point cloud of a forest. Each step describes a separate stage in the semi-automatic data processing method. These steps are explained further in the text below.

The data processing pipeline developed for this project utilises multiple open-source platforms to enable the measuring of trees from LiDAR point cloud data. Corresponding to the panels in figure 4, the pipeline can be summarised as follows, with the platform used for each step shown in bold:

- **a.** Each of the four TLS scans are co-registered or aligned by manually identifying common points (tie points; here reflective spheres placed in the forest) from the point cloud. This allows the co-registration of the four scans to form a single whole-plot point cloud. This is then exported as a **.las** file.
- **b.** The open-source platform **CloudCompare** is used to segment the study trees from the wider forest area. First, the study trees are identified, before manually using the segment tool in **CloudCompare** to remove extraneous points- those belonging to other trees or objects within the point cloud.
- **c.** The open-source **CloudCompare** plugin **3DFin** is then run on the segmented point cloud. This plugin segments individual trees from the whole-plot point cloud before determining the axis of orientation of the tree. Subsequently, a series of circles are fitted to the points representing the stem of the tree, at a user-defined interval (here set as 0.2 m), from a user-defined start point (here 0.3 m). This process outputs trees' DBH, highest point, and the diameter and X, Y, Z co-ordinates of each fitted section to a **.csv** file.
- **d.** Using **RStudio,** a script was devised to enable the measuring of tree sagitta (sweep), taper and lean according to algorithmic processing of the X, Y, Z co-co-ordinates of stem sections.

e. Again in **Rstudio**, code for the determination of optimal sawlog product output from trees was devised. This method applied the calculations of sagitta determined in the previous step and each log's position within a tree to criteria for log selection. Using this process, the suitability of a 4.8m green sawlog was assessed. If this was not present, then a 4.8m red sawlog was proposed. If this was not present, then the presence of a 3.6m green sawlog was tested for, and so on and so forth. The final length was 2.4m.
f. The volume of each selected sawlog was then calculated using the equation for the volume of the frustum of a cone- a cone with no point, effectively a tapered cylinder- in order to accurately calculate log volume. Using this data, log value was calculated using 2023 sawlog price data.

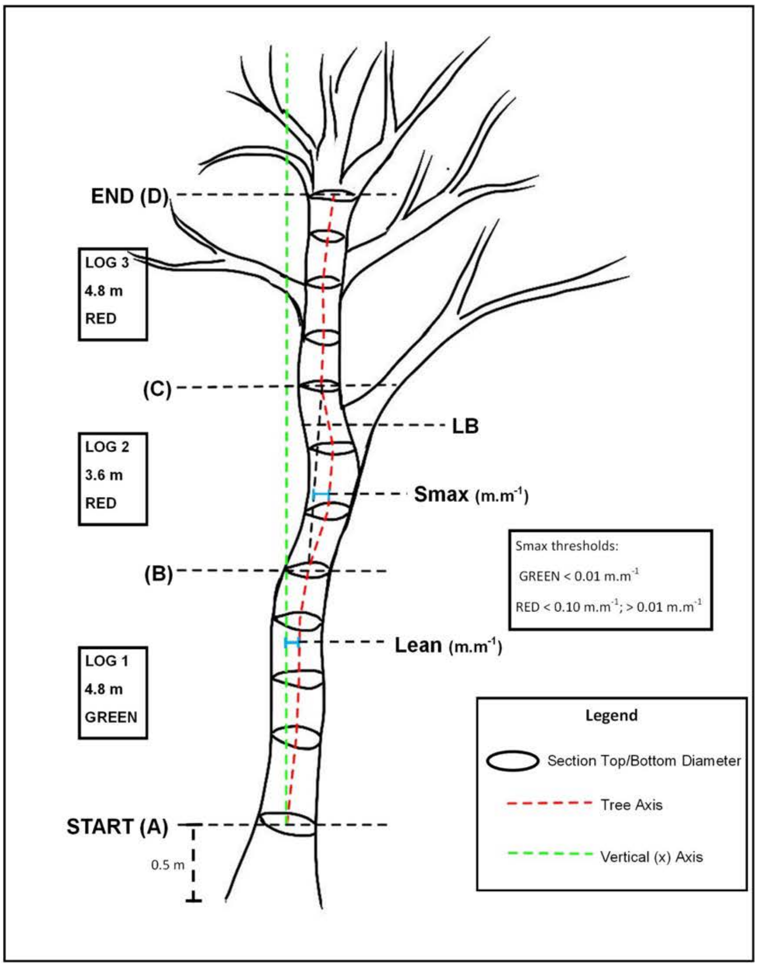

Figure 5: This diagram illustrates how logs are selected from tree stem measurements to determine the best sawlog length and grade. The process begins at point (A), where a 4.8 m log is tested. If it meets the straightness and positioning criteria, it is selected, with its endpoint at (B). The next log is then tested from (B), and this continues up to the final section (D). Straightness is measured as the maximum sagitta, or Smax; the greatest deviation from a perfectly straight line, calculated as the maximum distance from the log's centre to the tree's centre. Log volume is estimated using the frustum of a cone equation, based on the stem's diameter measurements (A, B, C, D) and the length of each log.

Discussion

LiDAR Measurements

The results of this study showed that it is possible to obtain measurements of key tree stem metrics relating to timber properties via the processing of LiDAR point clouds of the surveyed plots. The values for tree DBH obtained using both the manual and TLS measurement methods were highly similar. The agreement between the two methods' height measurements was slightly less, as were taper, sweep and lean measurements.

These measurements of stem diameter, taper, sweep and lean were then input into a sawlog determination algorithm which tested the suitability of specific operational sawlog lengths (2.4 m, 3.6 m or 4.8 m) and grade (red or green) based on input parameters. Longer and higher-quality sawlogs were the first to be tested, followed by the next shortest. In this way it was possible to preferentially select the highest-quality, longest sawlogs from the tree. Once a sawlog was selected, the end point of this sawlog was used as the start point of the next sawlog. Using this method it was possible to estimate the sawlogs harvestable from each tree.

Following the application of this method to each of the 55 surveyed trees, the value of each sawlog was found by calculating the value of each individual sawlog by multiplying its volume (m^3) by the benchmark price (price per metre cubed) obtained from sales data from 2023.

Using this method, this study was successful in estimating the potential timber product value of standing trees in a range of woodland environments. This demonstrates a potential use of LiDAR instruments for the estimation of tree timber value in complex woodlands. In addition to this, TLS' precise measurements enable the measurement of additional metrics difficult to measure using conventional measurement instruments, therefore presenting a methodology for the estimation of timber product output in addition to traditional measurements of stand volume.

Limitations of LiDAR-Based Measurements

There are both technological and practical limitations to the uptake and use of LiDAR measurements for forestry applications. As explained above, the algorithms used to process point cloud data are restrictively complex. Users of these algorithms therefore require extensive training and expertise, and as such, the processing of point cloud data is highly time-consuming. Overcoming this obstacle would require the development of an automated point cloud processing algorithm to enable the automatic determination of tree size and form from LiDAR data.

In addition to this, the collection of LiDAR point cloud data is practically complex and similarly requires a trained professional. To completely sample a survey area, several scans must be carried out, using artificial references - spheres or reflective targets - to co-register or merge these scans. These references must be appropriately placed in the survey area. Furthermore, LiDAR data collection is highly sensitive to weather conditions. Wind speeds of more than 10 mph will cause movement of trees, resulting in excessive noise in point clouds. Whilst some scanners are able to withstand rainy conditions, others are not, and water droplets within scans can cause errors in reconstruction of objects as well as visual noise. The weather window suitable for data collection is therefore relatively narrow.

Conclusions and Future Directions

This study showed that it is possible to use the measurements derived from terrestrial LiDAR point clouds to measure fine-scale variation in standing tree stem form. This data was then used to predict operational sawlog outputs from these trees, which has significant implications for the modernisation of silvicultural surveying techniques. Using this technology, it would be possible to vastly improve the precision of sawlog procurement from forests, streamlining the procurement process and increasing the proportion of sawlogs being used as higher-value products such as construction timber, locking up the carbon sequestered by the tree for a longer time period.

Whilst this study demonstrated this application of LiDAR to be possible, significant development is needed before it can be fully integrated into real-world forest management. To maximise its impact, LiDAR point cloud processing must be fully automated, enabling widespread adoption, greatly improving surveying efficiency and enabling better value capture from woodlands.

Bibliography/Reading List

1. Welsh Government. Net Zero Wales Carbon Budget 2 2021-25. (2021).
2. Newnham, G. J. et al. Terrestrial Laser Scanning for Plot-Scale Forest Measurement. Curr Forestry Rep 1, 239–251 (2015).
3. Liang, X. et al. Terrestrial laser scanning in forest inventories. ISPRS Journal of Photogrammetry and Remote Sensing 115, 63–77 (2016).
4. Thies, M. & Spiecker, H. EVALUATION AND FUTURE PROSPECTS OF TERRESTRIAL LASER SCANNING FOR STANDARDIZED FOREST INVENTORIES. (2004).
5. Calders, K. et al. Terrestrial laser scanning in forest ecology: Expanding the horizon. Remote Sensing of Environment 251, 112102 (2020).
6. Disney, M. Terrestrial LiDAR: a three-dimensional revolution in how we look at trees. New Phytologist 222, 1736–1741 (2019).
7. Calders, K. et al. Laser scanning reveals potential underestimation of biomass carbon in temperate forest. Ecological Solutions and Evidence 3, e12197 (2022).
8. Prendes, C. et al. Automatic Assessment of Individual Stem Shape Parameters in Forest Stands from TLS Point Clouds: Application in Pinus pinaster. Forests 13, 431 (2022).
9. Gonzalez de Tanago, J. et al. Estimation of above-ground biomass of large tropical trees with terrestrial LiDAR. Methods in Ecology and Evolution 9, 223–234 (2018).
10. Murphy, G. E., Acuna, M. A. & Dumbrell, I. Tree value and log product yield determination in radiata pine (Pinus radiata) plantations in Australia: comparisons of terrestrial laser scanning with a forest inventory system and manual measurements. Can. J. For. Res. 40, 2223–2233 (2010).
11. Pyörälä, J. et al. Assessing log geometry and wood quality in standing timber using terrestrial laser-scanning point clouds. Forestry: An International Journal of Forest Research 92, 177–187 (2019).
12. van Leeuwen, M. et al. Assessment of standing wood and fiber quality using ground and airborne laser scanning: A review. Forest Ecology and Management 261, 1467–1478 (2011).
13. Åkerblom, M., Raumonen, P., Mäkipää, R. & Kaasalainen, M. Automatic tree species recognition with quantitative structure models. Remote Sensing of Environment 191, 1–12 (2017).
14. Alvites, C. et al. Terrestrial Laser Scanning for Quantifying Timber Assortments from Standing Trees in a Mixed and Multi-Layered Mediterranean Forest. Remote Sensing 13, 4265 (2021).
15. Li, J. et al. Real-time automated forest field inventory using a compact low-cost helmet-based laser scanning system. International Journal of Applied Earth Observation and Geoinformation 118, 103299 (2023).