Evaluating the Accuracy of Pedunculate Oak Tree Volume Estimates Using Static Terrestrial and Mobile Personal Laser Scanning

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Abstract

Tree volume estimation is fundamental to forest management and inventory, yet traditional methods rely on allometric equations that introduce significant uncertainties due to generalized relationships and measurement limitations. This study evaluates the accuracy of mobile personal laser scanning (PLS) technology for tree volume estimation in pedunculate oak (*Quercus robur* L.) forests through a controlled comparison framework. Field work was conducted in January 2025 under optimal leaf-off conditions in a lowland oak stand in central Croatia. Three morphologically typical mature oak trees were selected within a single plot to enable controlled comparison while minimizing environmental variability. Data was acquired using PLS Faro Orbis Scanner, emphasizing complete stem coverage from multiple azimuths to support robust SLAM trajectory estimation and minimize occlusion effects. Three principal volume estimation approaches were evaluated: (i) sectioning volume obtained after felling, serving as the operational reference; (ii) PLS Schumacher-Hall volume, computed from LiDAR derived DBH and total height using established allometric relationships; and (iii) PLS Trunk Volume, computed directly from point cloud data using LiDAR360's trunk slicing workflow. Following PLS data acquisition, target trees were felled and bucked into contiguous sections, with length and end diameters recorded for each section to compute reference volumes. The sectioning dataset was treated as an operational reference rather than absolute ground truth, acknowledging potential reconstruction errors due to field conditions and occasional stem breakage. The study reveals important trade offs between measurement accuracy, operational efficiency, and methodological complexity, with sectioning volume providing the most direct measurement approach by eliminating remote sensing processing uncertainties. The research establishes a robust methodological framework for evaluating PLS performance in oak forests while highlighting both significant potential and current limitations of mobile laser scanning for operational forest inventory applications.

1. Introduction

Tree volume estimation is fundamental to forest management, inventory, and carbon accounting, serving as a critical parameter for sustainable forest resource planning and utilization. Traditional forest inventory methods rely on allometric equations that utilize easily measurable variables such as Diameter at Breast Height (DBH) and tree height to estimate tree volume (Rojas-García et al. 2015). However, these methods are labour-intensive, time-consuming, and expensive. Therefore, they are limited to small sampling areas and low temporal resolution. Furthermore, the accuracy of field measurements can be influenced by a number of potential errors. This is especially true for individual tree height measurements, which commonly produce lower accuracy and precision than DBH measurements (Luoma et al. 2017), mainly due to the limited visibility of treetops, especially in more complex forest environments (Liang et al. 2022). Moreover, tree heights are the costliest data to collect in a practical forest inventory, and therefore they are usually measured only on a selected number of trees within sample plots, and statistical modelling (DBH height) is required for non-measured trees. All the above mentioned and the generalized nature of allometric relationships for indirect tree volume estimation often introduce significant uncertainties.

The advancement of close-range remote sensing technologies has opened new possibilities for direct and precise estimation of tree attributes, including volume (Åkerblom and Kaitaniemi 2021). Among these technologies, terrestrial laser scanning (TLS) and mobile personal laser scanning (PLS) have emerged as particularly promising tools for forest inventory applications (Gollob, Ritter, and Nothdurft 2020). TLS provides high-precision three-dimensional point clouds that can capture detailed tree structure and the most accurate estimation of the main tree attributes, such as DBH and tree height (Weiser et al. 2022), while PLS offers the advantage of mobility and efficiency in data collection (Yang et al. 2024). Personal laser scanning has proven capable of directly capturing key tree attributes such as stem position, DBH, tree height, and stem curve, which are critical inputs for volumetric modelling (Balenović et al. 2020). Furthermore, certain but limited research revealed that high-end level PLS instruments can provide comparable estimation accuracy of the main tree attributes as TLS. Therefore, extensive research on the possibility of the application of PLS technology in forest inventory is required.

Pedunculate oak (*Quercus robur* L.) forests represent one of the most economically and ecologically important forest ecosystems in Central Europe (Mölder et al. 2019). These forests are characterized by complex canopy structures and irregular stem forms that pose challenges for accurate volume estimation using traditional methods. The application of laser scanning technologies in oak forests has shown promising results, but comparative studies between different scanning approaches and their validation against reference measurements remain limited (Stovall et al. 2023).

This preliminary study aims to evaluate the accuracy of PLS-based volume estimates of pedunculate oak trees and compare them with conventional field-based methods. Two different PLS-based volume estimates were evaluated: (i) indirectly computed from estimated DBH and tree height using Schumacher–Hall equation, and (ii) directly estimated from the point cloud. Also, tree volumes were estimated indirectly using two different

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conventional field-based methods: (i) using Schumacher–Hall equation and DBH and tree heights estimates, and (ii) using local tariff and DBH estimates. Following scanning and field measurements, the selected trees were felled and measured section-wise to determine the actual merchantable volume. These measurements served as reference ground-truth data for evaluating the accuracy of the PLS-based and conventional, field-based tree volume estimates.

2. Materials and Methods

2.1 Study area

The research was conducted in a 109-years-old, lowland pedunculate oak forest located in central Croatia, 75 km east of Zagreb (45°53'27"N, 16°41'03"E; 107 m a.s.l.). This forest land is state-owned and actively managed according to sustainable principles. One of the main reasons for the selection of this forest land for this research is that it is in the regeneration phase, during which regeneration felling is usually conducted. Three oak trees were selected within this land based on their representativeness of the local forest structure and their accessibility and suitability for feeling and comprehensive PLS protocols (Figure 1). The selected trees exhibited typical oak morphology with irregular branching patterns and variable stem forms, providing a realistic test case for PLS-based volume estimates.

Figure 1. Three selected pedunculate oak trees.

2.2 Data Collection

Both field and PLS data were collected during the leaf-off conditions in January 2025. Firstly, the DBH of each tree was measured manually using a calliper with a cm precision, while the tree height was measured using the ultrasonic hypsometer Haglöf Vertex IV instrument.

PLS data were collected using the FARO Orbis scanner (FARO Technologies Inc., Lake Mary, Florida, USA). The technical specifications of the Faro Orbis include:

- Detection range: 120 m
- Data collection rate: 640,000 points per second
- Number of LIDAR channels: 32
- Precision: 5 mm
- Flash scan resolution: 19 million points
- Flash scan accuracy: 13 mm at 10 m distance
- Laser safety classification: Class 1 (IEC EN60825-1)
- Operating temperature range: 0°C to +40°C

PLS Data collection involved systematic movement around each target tree while maintaining optimal scanning distances and angles to capture detailed tree structure.

Following field and PLS data acquisitions, the selected trees were felled and measured section-wise to determine the actual merchantable volume. For every section up to a diameter of 7 cm overbark, length and large- and small-end diameters were recorded (Figure 3). Section volumes were computed and summed to obtain total merchantable stem volume (up to a diameter of 7 cm overbark) for each tree. Because field conditions (low temperatures) and occasional branches breakage (Figure 4) could introduce certain reconstruction errors during section-wise measurement, the sectioning dataset should be treated as an operational reference rather than an absolute ground truth.

Figure 2. Section-wise measurement of the felled trees for the determination of the actual merchantable volume.

Figure 3. The example of branches breaking that occurs during tree felling which could introduce certain errors in section-wise measurement.

2.3 PLS data processing

Firstly, PLS data were pre-processed using the FARO Connect software and extracted in LAS format. For PLS data processing (point cloud normalization, tree segmentation) and extraction of the main tree attributes (DBH, tree height, tree volume) LiDAR360 v8.0 software (GreenValley International, Berkeley, California, USA) was used (Figure 5).
DBH and tree height of each tree were semi-automatically estimated. DBH was first approximately determined by the operator and then approximated by the Fit-by-circle method of the software algorithm. The Fit-by-circle method approximates DBH using the least squares method to fit a circle from the x-y coordinates of input points. Stems fitted by the circle method were used as seed points for individual tree segmentation. Tree heights were automatically estimated within the segmentation process and then manually (visually) checked for any errors.
Besides semi-automatically estimated DBH and tree heights, the volume of each tree was automatically, i.e., directly estimated using 'Trunk Volume' workflow estimates volume by slicing the stem horizontally at fixed vertical intervals fitting a circular model to the stem cross-section in each slice, and summing the volumes of adjacent cylindrical/frustum elements along the bole. This approach yields a geometric aggregation of slice-wise stem volumes derived from the point cloud without explicit branch topology reconstruction. For quality assurance, slices with insufficient support or unstable fits were flagged and, where necessary, re-estimated using neighbouring context or excluded under pre-specified criteria.

Figure 4. PLS derived point cloud of three selected pedunculate oak trees.

2.4 Data computation

Table 1. provides a detailed description of five different merchantable tree volume estimates (up to a diameter of 7 cm overbark).

Abbreviation	Method	Description of tree volume computation
V_{REF}	Field-based; reference, ground-truth	Section-wise measurement of the felled trees up to a diameter of 7 cm overbark
V_{TAR}	Conventional field-based; standardized method in operational forest inventory	A combination of DBH measurements using a calliper and the local tariff (one-entry table) from the forest management plan
V_{S-H}	Conventional field-based	A combination of DBH measurements using a calliper and tree height estimates using a Vertex hypsometer and Schumacher–Hall equation
V_{PLS-I}	PLS-based	Indirectly estimated using a semi-automatically estimated DBH and tree height from PLS data and Schumacher–Hall equation
V_{PLS-D}	PLS-based	Directly, automatically estimated using the 'Trunk Volume' software workflow

Table 1. Description of five different merchantable tree volume estimates (up to a diameter of 7 cm overbark)

The form of the Schumacher-Hall equation applied for tree volume estimation for V_{S-H} and V_{PLS-I} using DBH and tree height estimates is as follows:

$$V = a \times DBH^b \times H^c$$

where V is a tree volume (m^3),
DBH is a diameter at breast height (cm),
H is a tree height,
a, b, c are species-specific regression coefficients.

The Schumacher-Hall formula is a widely used allometric equation that relates tree volume to easily measurable parameters. The logarithmic transformation of this equation provides a linear relationship that can be calibrated for specific species and growing conditions.

3. Results

The results of field- and PLS-based measurements of DBH and tree heights for each tree used for indirect calculation of tree volumes with different methods (V_{TAR}, V_{S-H}, V_{PLS-I}) are shown in Table 2.

	Field based measurements			PLS-based measurements		
Tree ID	1	2	3	1	2	3
DBH (cm)	86.4	74.1	60.3	84.03	71.8	60.18
H (m)	36	36.4	33	36.7	36.4	33.6

Table 2. Field- and PLS-based measurements of DBH and tree heights

Tree volume estimates obtained by different methods (V_{REF}, V_{TAR}, V_{S-H}, V_{PLS-I}, V_{PLS-D}) are presented in Figure 5, while differences between the four evaluated methods (V_{TAR}, V_{S-H}, V_{PLS-I}, V_{PLS-D}) and the reference ground-truth data (V_{REF}) are presented in Table 3.

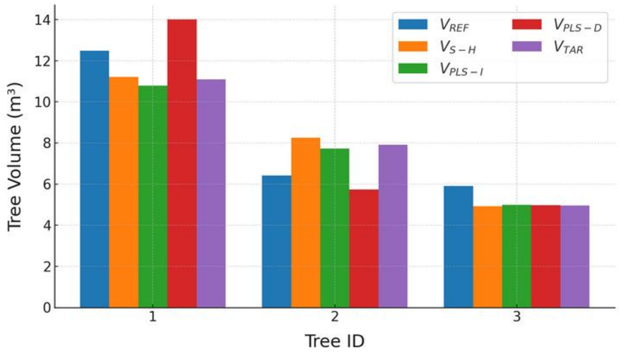

Figure 5. Comparison of tree volume estimates by method.

Tree ID	V_{TAR} (m³ (%))	V_{S-H} (m³ (%))	V_{PLS-I} (m³ (%))	V_{PLS-D} (m³ (%))
1	-1,38 (-11,06)	-1.26 (-10.10)	-1,66 (-13,31)	1,55 (12,41)
2	1,50 (23,47)	1.84 (28.76)	1,37 (21,38)	-0,67 (-10,42)
3	-0,94 (-15,94)	-0.97 (-16.51)	-0,85 (-14,44)	-0,92 (-15,60)

Table 3. Differences between the four evaluated methods (V_{TAR}, V_{S-H}, V_{PLS-I}, V_{PLS-D}) and the reference ground-truth data (V_{REF})

Tree volume estimates obtained from the conventional field-based method (V_{TAR}, V_{S-H}) and the two PLS-based approaches (V_{PLS-I} and V_{PLS-D}) showed clear deviations when compared to the reference volumes (V_{REF}) derived from destructive wise-sectioning.

Both V_{S-H} and the indirect PLS method (V_{PLS-I}) followed a similar pattern. They consistently underestimated the volume of the largest and the smallest tree, while at the same time overestimating the volume of the medium-sized tree. This indicates that these two approaches behaved in a comparable way, with PLS-indirect achieving accuracy levels close to the conventional field-based approach.

When comparing the conventional field-based approach (V_{REF}) and the indirect PLS method (V_{PLS-I}), their differences were relatively small. This close agreement can be explained by the fact that both methods rely on the same underlying Schumacher-Hall allometric equation, with the primary distinction being how tree dimensions are obtained: manually in the field or extracted from PLS data. As a result, the two approaches inherit similar strengths and limitations of the allometric model leading to comparable outcomes. This underlines that indirect PLS method, when paired with the Schumacher-Hall model, can function as a viable substitute for traditional field measurements while offering the added benefits of efficiency and non-destructive data collection.

The tariff-based method (V_{TAR}) produced results that were in some cases closer to the reference than those obtained with the Schumacher–Hall approach. However, this should be interpreted with caution, as tariff tables are generally based on historical averages and do not reflect current stand structures or individual tree variability. While the deviations observed here were not always the largest, the method's outdated and inflexible nature limits its relevance for modern operational inventory.

The direct PLS workflow (V_{PLS-D}) displayed a different tendency. Unlike the other methods, it overestimated the largest tree, but underestimated the volumes of the other two. This suggests that the automated trunk reconstruction process may be more sensitive to tree size and structure compared to the model-based approaches.

In summary, although none of the alternative methods matched the reference perfectly, the results revealed clear method-specific biases: the conventional and indirect PLS approaches behaved similarly, while the direct PLS workflow followed a distinct, opposite trend.

4. Discussion

The field work conducted in January 2025 under leaf-off conditions provided optimal circumstances for laser scanning in deciduous forest environments. The absence of foliage significantly reduced occlusion effects and enhanced point cloud penetration to stem surfaces, which is critical for accurate volume estimation (Calders et al. 2020). The selection of morphologically typical trees within a controlled plot design enabled robust comparative analysis while maintaining operational relevance for forest inventory applications.

One of the primary challenges in mobile laser scanning applications is achieving complete and uniform point cloud coverage of target objects (Jurjević et al. 2020). The emphasis on clear views of trunks and lower crowns while minimizing occlusion demonstrates the importance of strategic data collection protocols in forest environments. The SLAM trajectory estimation and downstream stem segmentation capabilities of modern PLS systems have advanced significantly, enabling reliable automated processing of complex forest point clouds. However, the quality of these automated processes remains dependent on the homogeneity of the initial point cloud data, emphasizing the critical importance of optimal field collection protocols.

The three principal stem-volume estimation approaches evaluated in this study represent different levels of measurement directness and technological sophistication. The sectioning volume obtained after felling serves as the operational reference, providing the most direct geometric measurement of actual stem volume. This approach, while destructive, eliminates many of the uncertainties associated with indirect estimation methods and provides a robust baseline for evaluating remote sensing technologies. The PLS Schumacher-Hall (V_{PLS-I}) volume estimation approach represents an indirect method that relies on allometric relationships between easily measurable tree dimensions (DBH and height). While this approach benefits from well-established species-specific coefficients, it inherently carries the uncertainties associated with generalized allometric equations. The accuracy of PLS-derived DBH and height measurements is crucial for this approach, as small measurement errors can propagate significantly in volume calculations due to the exponential nature of the allometric relationships.

The PLS Trunk Volume estimation using LiDAR360's trunk-slicing workflow represents a more direct approach to volume estimation from point cloud data. This method attempts to reconstruct stem geometry directly from three-dimensional point clouds, potentially capturing individual tree form variations that may not be adequately represented by generalized allometric equations. However, the accuracy of this approach is highly dependent on point cloud quality, density, and the performance of automated stem reconstruction algorithms. The sectioning methodology employed in this study follows established forestry practices for obtaining high-accuracy volume measurements. The systematic bucking of felled trees into contiguous sections, followed by precise measurement of section lengths and end diameters, provides a direct geometric approach to volume calculation that minimizes estimation uncertainties. The recognition of small reconstruction errors due to field conditions (low temperatures) and occasional stem breakage reflects the practical realities of operational forest inventory. Consequently, while sectioning serves as the best available benchmark, the influence of terrain and environmental conditions means that it should not be regarded as an absolute reference, but rather as a practical operational standard against which other methods can be evaluated.

The LiDAR360 trunk slicing workflow represents current evolved approach in automated stem volume estimation from point cloud data. However, several factors can influence the accuracy of these automated processing algorithms. Point cloud density and uniformity significantly affect the precision of stem boundary detection and cross-sectional area calculations (Xie et al. 2020). The automated detection and delineation of stem boundaries from point cloud data presents particular challenges in forest environments. Bark texture, branch attachments, and irregular stem forms can introduce noise and artifacts that affect volume calculations. Algorithm parameterization and calibration also play crucial roles in determining volume estimation accuracy. Default software settings may not be optimal for specific tree species or forest conditions, and species-specific calibration can significantly improve results (Nurunnabi et al. 2024). The demonstrated accuracy improvements of laser scanning methods over traditional forest inventory approaches have significant implications for operational forest management. Traditional methods relying on manual DBH measurements and local tariff tables, while cost-effective, often introduce substantial uncertainties due to the generalized nature of volume functions and measurement limitations. The efficiency advantages of PLS technology are particularly noteworthy for practical forest inventory applications.

The findings of this study highlight several areas for future research to further advance laser scanning applications in forest inventory. Comparative studies across different forest types, tree species, and stand conditions are needed to establish the broader applicability of these technologies. The development of species-specific and region-specific calibration procedures for volume estimation algorithms would enhance accuracy and operational reliability. Despite significant advances in SLAM-based mobile laser scanning, deriving reliable tree volume estimates remains a challenge. Wu et al. (2025) note that volume estimation is particularly sensitive to variations in forest structure, point cloud quality, and algorithm robustness, making it one of the more difficult attributes to obtain with high accuracy. This highlights the need for further methodological development and calibration to ensure operational applicability across diverse forest types.
Future research should examine data acquisition strategies such as appropriate point cloud densities and the integration of different scanning technologies to improve the volume estimates. Reducing the need for manual intervention while still meeting accuracy requirements by developing the automated workflows is the objective to strive for.

It should be noted that this study was based on a limited number of sample trees, which constrains the generalizability of the findings. To obtain more robust and widely applicable conclusions, future research should be conducted on larger and more diverse tree samples. More generally, careful acquisition of reference data is essential, as its reliability forms the basis for the accurate evaluation and validation of all volume estimation approaches.

In future research, Quantitative Structure Models (QSMs) should be investigated more thoroughly, as they provide a powerful means of deriving tree architecture and volume directly from point cloud data. Their potential for non-destructive and highly detailed volume estimation is clear, yet challenges remain in terms of point cloud requirements, algorithm calibration, and scalability across different species and forest conditions. Addressing these limitations through further methodological development could make QSMs a key tool in operational forest inventory (Fan et al. 2020)

5. Conclusions

This study evaluated the accuracy of pedunculate oak tree volume estimates obtained through sectioning, Schumacher–Hall models applied to both field and PLS measurements, and an algorithm for trunk volume estimation using LiDAR360 software. The results revealed clear trade-offs between accuracy, efficiency, and complexity. Sectioning provided the most direct, although not flawless, reference. The PLS Schumacher–Hall method showed strong potential for bridging remote sensing and traditional inventory techniques, while the trunk-slicing workflow represented the most advanced option but remained highly dependent on point cloud quality and algorithm performance.

Overall, mobile PLS enabled rapid and non-destructive data collection with reliable accuracy, demonstrating its value for operational forestry. Laser scanning holds significant promise for improving tree volume estimation, and future research should focus on refining algorithms and calibration procedures to fully realize its potential in diverse forest conditions.

References

Åkerblom, Markku, and Pekka Kaitaniemi. 2021. “Terrestrial laser scanning: a new standard of forest measuring and modelling?” *Annals of Botany* 128 (6): 653–62. https://doi.org/10.1093/aob/mcab111.

Balenović, Ivan, Xinlian Liang, Luka Jurjević, Juha Hyyppä, Ante Seletković, and Antero Kukko. 2020. “Hand-Held Personal Laser Scanning.” *Croatian Journal of Forest Engineering* 42 (1): 165–83. https://doi.org/10.5552/crojfe.2021.858.

Calders, Kim, Jennifer Adams, John Armston, Harm Bartholomeus, Sebastien Bauwens, Lisa Patrick Bentley, Jerome Chave, et al. 2020. “Terrestrial laser scanning in forest ecology: Expanding the horizon.” Remote Sensing of Environment 251 (September): 112102. https://doi.org/10.1016/j.rse.2020.112102.

Fan, Guangpeng, Liangliang Nan, Feixiang Chen, Yanqi Dong, Zhiming Wang, Hao Li, and Danyu Chen. 2020. “A New Quantitative Approach to Tree Attributes Estimation Based on LiDAR Point Clouds.” Remote Sensing 12 (11): 1779. https://doi.org/10.3390/rs12111779.

Gollob, Christoph, Tim Ritter, and Arne Nothdurft. 2020. “Forest Inventory With Long Range and High-Speed Personal Laser Scanning (PLS) and Simultaneous Localization and Mapping (SLAM) Technology.” *Remote Sensing* 12 (9): 1509. https://doi.org/10.3390/rs12091509.

Jurjević, Luka, Xinlian Liang, Mateo Gašparović, and Ivan Balenović. 2020. “Is Field-measured Tree Height as Reliable as Believed – Part II, a Comparison Study of Tree Height Estimates From Conventional Field Measurement and Low-cost Close-range Remote Sensing in a Deciduous Forest.” *ISPRS Journal of Photogrammetry and Remote Sensing* 169 (October): 227–41. https://doi.org/10.1016/j.isprsjprs.2020.09.014

Liang, Xinlian, Antero Kukko, Ivan Balenovic, Ninni Saarinen, Samuli Junttila, Ville Kankare, Markus Holopainen, et al. 2022. “Close-Range Remote Sensing of Forests: The State of the Art, Challenges, and Opportunities for Systems and Data Acquisitions.” *IEEE Geoscience and Remote Sensing Magazine* 10 (3): 32–71. https://doi.org/10.1109/mgrs.2022.3168135.

Luoma V, Saarinen N, Wulder MA, White JC, Vastaranta M, Holopainen M, Hyyppä J, 2017. Assessing Precision in Conventional Field Measurements of Individual Tree Attributes. Forests 8(2): 38. https://doi.org/10.3390/f8020038

Mölder, Andreas, Holger Sennhenn-Reulen, Christoph Fischer, Hendrik Rumpf, Egbert Schönfelder, Johannes Stockmann, and Ralf-Volker Nagel. 2019. “Success Factors for High-quality Oak Forest (Quercus Robur, Q. Petraea) Regeneration.” *Forest Ecosystems* 6 (1). https://doi.org/10.1186/s40663-019-0206-y.

Nurunnabi, Abdul, Felicia Teferle, Ana Novo, Jesús Balado, and Emmett Ientilucci. 2024. “Derivation of Tree Stem Curve and Volume Using Point Clouds.” the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences/International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XLVIII-4/W11-2024 (June): 81–88. https://doi.org/10.5194/isprs-archives-xlviii-4-w11-2024-81-2024.

Rojas-García, Fabiola, Bernardus H. J. De Jong, Pablo Martínez-Zurimendí, and Fernando Paz-Pellat. 2015. “Database of 478 Allometric Equations to Estimate Biomass for Mexican Trees and Forests.” *Annals of Forest Science* 72 (6): 835–64. https://doi.org/10.1007/s13595-015-0456-y.

Stovall, Atticus E L, David W MacFarlane, Debbie Crawford, Tom Jovanovic, Jereme Frank, and Cris Brack. 2023. “Comparing Mobile and Terrestrial Laser Scanning for Measuring and Modelling Tree Stem Taper.” *Forestry an International Journal of Forest Research* 96 (5): 705–17. https://doi.org/10.1093/forestry/cpad012.

Weiser, Hannah, Jannika Schäfer, Lukas Winiwarter, Nina Krašovec, Fabian E. Fassnacht, and Bernhard Höfle. 2022. “Individual Tree Point Clouds and Tree Measurements From Multi-platform Laser Scanning in German Forests.” Earth System Science Data 14 (7): 2989–3012. https://doi.org/10.5194/essd-14-2989-2022.

Xie, Yuyang, Jie Zhang, Xiangwu Chen, Shuxin Pang, Hui Zeng, and Zehao Shen. 2020. “Accuracy Assessment and Error Analysis for Diameter at Breast Height Measurement of Trees Obtained Using a Novel Backpack LiDAR System.” Forest Ecosystems 7 (1). https://doi.org/10.1186/s40663-020-00237-0.

Yang, Jinming, Wenwen Yuan, Huicui Lu, Yuehan Liu, Yongkang Wang, Letong Sun, Shimei Li, and Haifang Li. 2024. “Assessing the Performance of Handheld Laser Scanning for Individual Tree Mapping in an Urban Area.” *Forests* 15 (4): 575. https://doi.org/10.3390/f15040575.