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Integrating ARKit 6 (Arboreal Forest app) in woodland mensuration: A case study in the Zagros woodlands, Iran

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Abstract As augmented reality (AR) technology continues to evolve, its application in forestry measurement is gaining increasing attention. While previous research has largely focused on diameter at breast height (DBH) measurements, expanding AR-based tools to other tree parameters is essential for assessing forest structure, biomass, and growth. This study evaluates the effectiveness of ARKit 6 (Arboreal Forest app, AF), a LiDAR-integrated mobile tool, for measuring tree height and crown diameter, by comparing its measurements with those of TruPulse 360B (TP), a professional-grade laser rangefinder. A statistical framework employing probability and cumulative distribution functions was applied to 215 broadleaved and coniferous trees, with goodness-of-fit tests (Kolmogorov-Smirnov and Anderson-Darling) indicating that Weibull and Log-Normal distributions best described the measurements. Agreement between tools was assessed using Bland-Altman analysis and error metrics including bias, mean absolute error (MAE), and root mean square error (RMSE). For height, the bias was -0.01 m, MAE 0.125 m, and RMSE 0.211 m, while for crown diameter, bias -0.59 m, MAE 2.02 m, and RMSE 2.70 m, indicating strong agreement between AF and TP. Descriptive statistics indicated similar means, standard deviations, and skewness values, suggesting that AF provides measurements comparable to TP. Minor differences in kurtosis and skewness suggest how each tool handles extreme values. These findings highlight AF as a cost-efficient and reliable alternative to professional-grade tools for tree height and crown diameter estimation. As AR technology evolves, its role in forestry is expected to expand toward real-time data integration, modeling, and ecological assessments.

Keywords: crown diameter, cumulative distribution functions (CDFs), height, LiDAR, probability density functions (PDF), TruPulse 360B.

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Introduction

Accurately estimating tree biophysical parameters is essential in forest management and conservation, as these parameters provide critical insights into tree growth, forest health, and biomass (Yang et al. 2023). They serve as key indicators for assessing tree vigor and environmental conditions, enabling researchers to monitor biodiversity and habitat structure (Zhao et al. 2023).

Biophysical parameters such as crown size and tree height are particularly important in forest management, where they guide timber valuation and thinning operations to maintain ecological balance and economic viability (Yang et al. 2023). Moreover, these measurements play a critical role in estimating carbon stocks, which are crucial for understanding carbon sequestration and modeling climate change mitigation strategies (Su et al. 2025). By providing foundational data for ecological studies, forest inventories, and carbon accounting, precise measurements of tree dimensions support both scientific research and sustainable forest management practices (Atkins et al. 2023; Zhao et al. 2023; Su et al. 2025).

Traditional tools such as calipers and clinometers have been foundational in forest mensuration for measuring tree dimensions, but their manual nature makes the process labor-intensive and time-consuming and each tree requires individual attention, slowing the process, especially in dense forests. These tools demand significant physical effort, including navigating rough terrain and dense vegetation to set up tools and obtain accurate measurements. Skilled operators are essential for using these tools effectively, as they require knowledge of angles, distances, and trigonometric principles, yet they remain prone to human error from misalignments or misjudgments (Clark et al. 1999; Liang et al. 2016; Luoma et al. 2017). The challenges compound in large-scale forest inventories, where measuring hundreds or thousands of trees can lead to tiredness, reduced accuracy, and increased time requirements. Environmental factors, such as limited visibility in dense forests or obstacles in the field, further complicate the process.

Digital or mobile tools have mitigated some of these challenges by reducing the need to be physically close to each tree and facilitating faster data collection (Vastaranta et al. 2015; Gollob et al. 2021; Tatsumi et al. 2023). However, they still require the operator to locate and scan individual trees, and their efficiency and accuracy in different forest conditions must be systematically evaluated. Moreover, occlusion remains a stand-specific limitation, if a treetop is hidden due to canopy structure or understory, it cannot be observed even with digital tools. Field navigation and scanning still require operator effort, and the safety, efficiency, and accuracy of these systems vary depending on stand structure and terrain conditions (Borz et al. 2022, 2024). These observations have highlighted the need for investigating the efficiency and reliability of both traditional and digital measurement approaches.

Advanced tools like LiDAR (Light Detection and Ranging) have significantly improved the precision of forest mensuration by capturing complex three-dimensional data about tree structures and forest stands. Unlike traditional manual methods, LiDAR can quickly generate detailed maps of tree crown dimensions, heights, and canopy cover over large areas, making it valuable for forest mensuration, carbon stock estimation, and ecological studies. However, despite its capabilities, conventional terrestrial and airborne LiDAR comes with several challenges.

The high costs of the equipment and software, as well as the operational expenses of using terrestrial or airborne platforms for data collection, make it a prohibitively expensive option for many organizations. Additionally, they generate large volumes of complex data that require specialized knowledge in GIS, remote sensing, and data analysis, which may be inaccessible to smaller teams or individuals. The need for costly infrastructure and regulatory restrictions further limit its accessibility, particularly for smaller or resource-limited organizations. Furthermore, while terrestrial and airborne LiDAR are highly efficient for capturing detailed structural information, their cost and complexity limit their suitability for small-scale or routine forest monitoring.

Terrestrial LiDAR is typically restricted to plot-level analyses due to the time and effort required for scanning, whereas airborne LiDAR, though capable of covering larger areas, involves substantial operational expenses and data-processing demands (Dalla Corte et al. 2020; Tatsumi et al. 2023; Chioni et al. 2023; Ferrara et al. 2023).

These barriers highlight the critical need for affordable, accessible, and precise alternatives in forest mensuration. Technologies like augmented reality (AR), which can be used on common devices such as smartphones or tablets, provide a promising solution. While they may not yet match the precision of terrestrial and airborne LiDAR, they offer a cost-effective, user-friendly alternative for smaller-scale practitioners and organizations. Affordable yet precise measurement technologies are essential to ensure that a wide range of users can engage in accurate forest management, inventory, and monitoring without the prohibitive costs associated with advanced systems like LiDAR (Coops et al. 2021; Tatsumi et al. 2023; Borz et al. 2024; Howie & De Stefano 2024; Magnuson et al. 2024).

ARKit, Apple AR framework, has emerged as a promising tool in various fields, including forestry. Available on widely used iOS devices like iPhones and iPads, ARKit considers a device camera, sensors, and processing power to overlay virtual information onto the real world. Its user-friendly nature, accessibility, and integration with consumer-grade devices make it an attractive option for forestry professionals and smaller organizations that may not have access to more expensive technologies such as LiDAR or drones. ARKit affordability is a key advantage, as it only requires an iPhone or iPad, making it a cost-effective alternative to traditional methods and advanced measurement tools. Additionally, its intuitive interface reduces the need for specialized training, simplifying fieldwork and eliminating the reliance on manual tools like calipers or clinometers (Gollob et al. 2021; Wang et al. 2022; Gülci et al. 2023).

In the literature, most studies (Celes et al. 2019; Wang et al. 2022; Song et al. 2023; Howie & De Stefano 2024) have compared AR-based estimations of biophysical parameters with traditional tools like calipers and tape meters, providing valuable insights into AR potential in forestry. However, comparison with more modern and precise forestry tools aligns with these previous studies but takes a step forward in assessing AR accuracy. Since these tools are specifically designed for field measurements, this approach offers a more rigorous evaluation of AR capabilities. While ARKit holds significant potential, its accuracy may be influenced by lighting conditions, obstructions, and other environmental conditions, making it essential to explore its performance against advanced tools like laser rangefinders. This comparison helps refine our understanding of AR strengths and limitations in professional forestry applications.

To better understand the variability in measurements taken using AR and other tools, the use of Probability Distribution Functions (PDFs) becomes essential. PDFs help model measurement variability, allowing researchers to estimate the consistency and reliability of different measurement tools. By fitting PDFs to collected data, one can evaluate how consistently a tool produces accurate measurements and how much variability is present. This process is particularly useful when comparing AR with modern tools like TruPulse360B (TP) or advanced systems like LiDAR. Fitting PDFs also helps quantify measurement errors in tree attribute estimation, offering a statistical foundation for evaluating tool performance (Liu et al. 2004; Gorgoso-Varela et al. 2024). Furthermore, applying such analyses allows for objective evaluation of the precision and reliability of consumer-grade tools like AF in comparison to professional-grade instruments such as TP, providing deeper insights into their measurement robustness and potential practical use.

Despite numerous studies comparing AR-based measurements with traditional tools (Tatsumi et al. 2023; Howie & De Stefano 2024; Su et al. 2024), there remains a notable gap in quantitative analyses that use statistical modeling such as PDFs to describe and interpret measurement variability. Most prior work has focused primarily on DBH measurements using

AF (Sandim et al. 2023; Borz et al. 2024; Howie & De Stefano 2024), whereas variability in other attributes has not been systematically examined. PDFs provide a robust statistical framework for modeling the uncertainties arising from tool limitations, environmental conditions, and human error, thereby providing a clearer, statistically grounded comparison of measurement reliability under real-world field conditions.

While AR technologies have gained widespread attention for diameter at breast height (DBH) measurements (Wang et al. 2022; Ahamed et al. 2023; Broz et al. 2024; Howie & De Stefano 2024; Su et al. 2024), research on their application for measuring other key tree biophysical parameters remains limited. These parameters, such as tree height and crown dimensions, are essential for tree and stand growth assessment and monitoring, yet they have not been extensively explored in AR-based studies. As a result, the full capabilities and limitations of AR in capturing these important parameters under diverse, real-world forest environments remain unclear. This gap underscores the need for direct, quantitative comparisons with established, precise laser-based measurement tools and the application of statistical methods to evaluate measurement variability. Addressing these gaps would provide a clearer understanding of AR potential in forestry, its strengths and weaknesses compared to field methods, and how its accuracy can be quantified and trusted across diverse field conditions.

The primary goal of this study is to evaluate the effectiveness of AR in forestry applications, specifically for tree crown diameter and height measurements, and compare it with an advanced LiDAR-based tool, TP, a well-established field instrument (Panagiotidis et al. 2016; Sadeghian et al. 2022). The study aims to determine whether the Arboreal Forest app (AF), which is based on ARKit 6 and utilizes LiDAR integrated into mobile devices, can achieve comparable precision and consistency to the TP. The main objectives are to (1) assess the measurement accuracy of AF relative to a professional-grade tool, and (2) analyze the variability and potential biases in measurements obtained from both instruments. The study also seeks to characterize the statistical behavior of measurement errors through distribution modeling to better understand tool performance under various conditions.

This study contributes to AR-based forestry research by focusing on tree height and crown attributes, complementing previous studies that mainly examined DBH measurements. Unlike previous studies that compared AR with traditional tools like diameter tapes and calipers, this study compares two laser-based measurement tools: the consumer-grade AF and the professional-grade TP, assessing AR reliability and practicality against a professional laser rangefinder. Additionally, the study introduces a statistical framework to analyze measurement variability, offering deeper insights into accuracy and precision beyond standard agreement analysis. This approach enhances the assessment of forestry tools, helping researchers, professionals, and policymakers choose cost-efficient and dependable alternatives for forest mensuration.

Material and methods

Study area

The study area is part of the Zagros woodlands, one of the most significant forest ecosystems in Iran, covering vast mountainous regions and playing a crucial role in soil conservation, water regulation, and supporting biodiversity. These woodlands are predominantly composed of Persian oak (*Quercus brantii* Lindl.), a keystone species vital for the ecological and socio-economic stability of the region (Erfanifard & Sheikholeslami 2017).

The current study focuses on five distinct forest sites within Lorestan province, western Iran. The sites included man-made forests within the Agricultural and Natural Resources Educational Complex of Lorestan University, located southwest of Khorramabad, features a flat landscape with uniform soil conditions and is primarily composed of planted conifers, including Bruce pine (*Picea pungens* Engelm.), silver cypress (*Cupressus arizonica* Greene), Mediterranean cypress (*Cupressus sempervirens* Lindl.).

The Darreh-Seyyed forests, situated in the southwest of Khorramabad, span 2080.9 ha and are characterized by natural oak-dominated woodlands.

The Chegeni forest area, located in the semi-humid and dry forest zone northwest of Lorestan, varies in elevation from 1050 to 1575 m and contains diverse native tree species.

The Shurab region forests near Khorramabad, at an elevation of 1200 m, are another key study site with natural oak populations.

Lastly, the Qaleh-Gol forests, located 35 kilometers south of Khorramabad, feature a cold semi-humid climate and a mix of native broadleaf species.

These five sites in the center of Zagros woodlands collectively provide a representative sampling of both broadleaved and coniferous species, ensuring a diverse dataset. This diversity allows for a more comprehensive evaluation of tree measurement accuracy across different environmental conditions and tree structures.

Field observations

A total of 215 single trees, including species such as Bruce pine, silver cypress, Mediterranean cypress, and Persian oak, were sampled. The selection of sample trees was based on their accessibility, health condition, and uniformity in structure.

For each tree, height was measured using the TP by aiming at the trunk base and at the top of the crown. The instrument internal inclinometer and rangefinder automatically computed total height from the difference in vertical angles and distances. Crown diameter was determined by measuring the horizontal distances between the two widest visible crown edges perpendicular to each other and averaging them to obtain the final crown width (Fig. 1 A).

Each measurement (height and crown diameter) was repeated three times under consistent field conditions, and the mean value was used in the analysis to minimize random error. Additionally, all collected data were cross-checked for accuracy and consistency, ensuring that they align with the overall objectives of the study.

The TP, a high-precision laser instrument widely recognized for forestry measurements, has a distance resolution of 10 cm, a slope accuracy of 0.25%, and an azimuth resolution of 1°. This device measures the horizontal distance to objects by determining the angle of inclination and azimuth, enabling the calculation of straight-line distances between two points with high precision (Follett et al. 2016; Sadeghian et al. 2022). A new TP laser rangefinder is priced at approximately $3300 on Amazon (31 January 2025). These advanced capabilities make it particularly suitable for use in rugged and densely vegetated forest environments, ensuring accurate and consistent data collection. The use of this precise instrument allowed for the collection of high-quality data, providing a strong foundation for subsequent analyses of the forest structure and composition.

ARKit-based measurements

AR technology was utilized in this study for tree measurements, employing the specialized AF, which is specifically designed for forest and tree analysis and optimized for iOS users. The application considers Apple ARKit 6 framework which integrates the LiDAR sensor of the iPhone 12 Pro to provide accurate measurements of tree dimensions such as height, diameter, and crown size. For this purpose, we used an iPhone 12 Pro smartphone, equipped with a 6.1-inch display and LiDAR technology, which supports ARKit 6. The iPhone 12 Pro LiDAR sensor is a time-of-flight (ToF) system with an effective range of approximately 5 meters, capable of generating high-resolution depth maps by emitting near-infrared laser pulses (Luetzenburg et al. 2021). The iPhone 12 Pro is available for approximately $1000 for a new model on Amazon (31 January 2025).

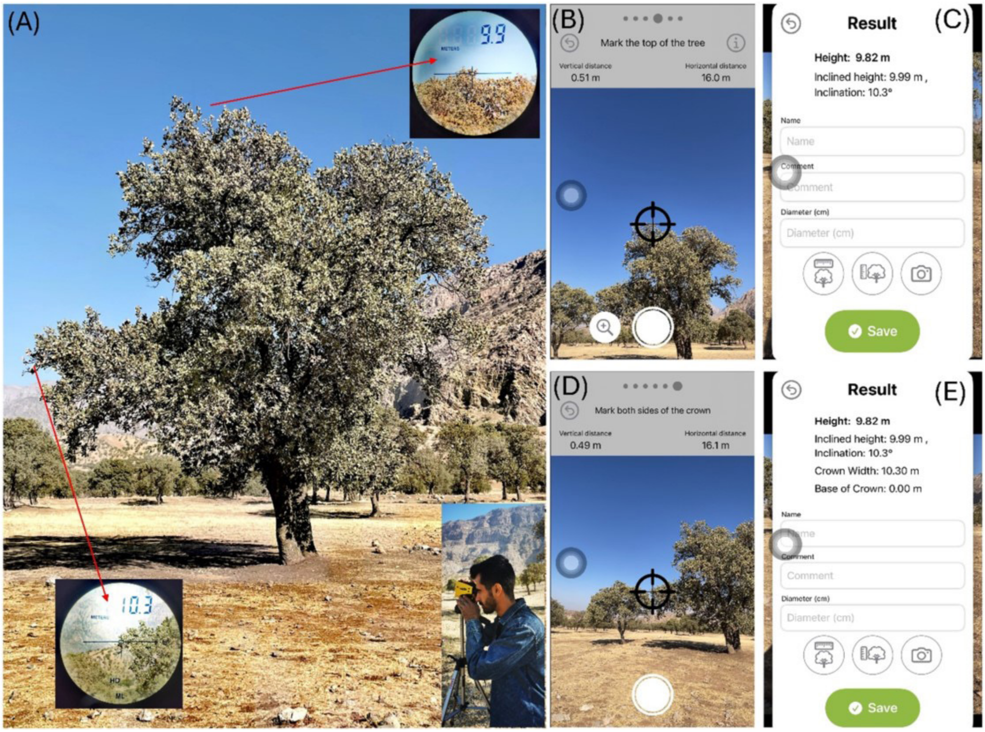
Measurements were conducted in the field by positioning the user at an average distance of 3–5 meters from each tree to ensure optimal LiDAR performance and consistency in data collection. To minimize potential bias and errors, a single trained individual performed all measurements. This approach eliminated variations in technique that might arise from multiple users and contributed to the reliability of the data. Prior to fieldwork, the individual was trained to use the AF and conducted several trial measurements to ensure familiarity with the device and application interface.

The measurement process involved aligning the AR-based tool with visible features of the trees. For each tree, height was measured by aligning the on-screen markers with the trunk base and the top of the crown, after which the AF automatically calculated total height (Fig. 1, B-C). Crown diameter was measured by tracing the widest horizontal extent of the crown, followed by a perpendicular measurement, and the two values were averaged to obtain the final diameter (Fig. 1, D-E). The AF provided real-time feedback during the measurements, ensuring precise alignment with the target tree and enabling corrections where necessary. These measurements were cross-referenced with laser-based data (using the TP) to validate the AF effectiveness and identify any discrepancies.

Methodology

To evaluate the performance of AF in measuring tree height and crown diameter compared to the TP, a rigorous statistical analysis was conducted using goodness-of-fit tests and probabilistic modeling. The methodology involved comparing the observed frequency distributions of tree measurements obtained using AF with the expected distributions derived from TP data.

Goodness-of-fit tests are statistical tools that compare the observed frequency distribution of a dataset with the expected frequency distribution based on a given probabilistic model. The null hypothesis (*H*0) in such tests assumes that the observed distribution does not differ significantly from the expected distribution. In this study, two goodness-of-fit tests were employed. Kolmogorov-Smirnov (KS) Test which is a non-parametric



Height: 9.82 m
Inclined height: 9.99 m ,
Inclination: 10.3°

Height: 9.82 m
Inclined height: 9.99 m ,
Inclination: 10.3°
Crown Width: 10.30 m
Base of Crown: 0.00 m

Figure 1 Measurement of tree attributes, i.e., height and crown diameter, using the TruPulse 360B (TP) and Arboreal Forest (AF) for a sample tree in Zagros woodlands (KhoramAbad, Iran). (A) Height (9.9 m) and crown diameter (10.3 m) measured with TP. (B-C) Height measurement using AF (9.82 m). (D-E) Crown diameter measurement using AF (10.30 m) for the same tree.

test evaluates the largest difference between the cumulative distribution functions (CDFs) of the observed and expected distributions. Anderson-Darling (AD) Test which focuses on the tails of the distribution, providing a more sensitive measure for detecting deviations from the expected distribution.

To model the variability and measurement errors of tree height and crown diameter, five statistical distributions were fitted to the data, i.e., Gamma Distribution (two-parameter), Exponential Distribution (single-parameter), Normal Distribution (two-parameter), Log-Normal Distribution (two-parameter), Weibull Distribution (two-parameter). Fitting multiple statistical distributions allows for a comprehensive understanding of measurement variability and errors by capturing different patterns in tree height and crown diameter data. This methodology provides flexibility in modeling non-normal data, improves the detection of biases and outliers, and enhances the robustness of the goodness-of-fit tests. By analyzing multiple distributions, the study ensures a more accurate comparison between AF and TP, making it adaptable across various forest environments and conditions. Overall, it strengthens the reliability and statistical validity of the results.

The functions and parameters of these distributions are detailed in Table 1. The parameters of the distributions were estimated using the maximum likelihood estimation (MLE) method. MLE is a robust statistical approach that estimates parameters by maximizing the likelihood function, ensuring that the observed data are most probable given the parameter values. While MLE often requires complex calculations, numerical methods were applied to obtain accurate estimates for the parameters of each distribution.

The goodness-of-fit and the parameters of the fitted distributions were calculated using R statistical software. The workflow involved the following steps. Measurements from AF and TP were organized for comparative analysis. Observed data from both tools were fitted to the five selected statistical distributions. MLE was applied to estimate distribution parameters, such as the mean, standard deviation, and skewness. The KS and AD tests were performed to evaluate how well the observed data fit the expected distributions. The goodness-of-fit tests provided a quantitative assessment of how closely AF measurements aligned with TP measurements.

By analyzing the fitted distribution parameters (e.g., mean, standard deviation, skewness, kurtosis), the study identified the statistical characteristics of measurement variability and biases for both tools. This methodological framework provided a robust approach for comparing AF and TP measurements, enabling an evaluation of AF reliability and its potential as a practical alternative in forestry applications.

In addition to using probability distribution fitting to characterize the statistical behavior and variability of the measurement data, we

Table 1 The probability distribution functions (PDFs) implemented to model tree height and crown diameter (*x*) in this study.

PDFs	Density function	Parameter
Gamma	$f(x) = \frac{x^{\alpha-1}}{\beta^{\alpha}\Gamma(\alpha)} e^{\left(-x/\beta\right)}$	α: continuous shape parameter β: continuous scale parameter $\Gamma(\alpha)$: gamma function
Exponential	$f(x) = \lambda e^{(-\lambda x)}$	λ: continuous inverse scale parameter $x \geq 0$
Normal	$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} e^{\left[-(x-\mu)^2/2\sigma^2\right]}$	σ: continuous scale parameter μ: continuous location parameter
Lognormal	$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} e^{\left[-(lnx-\mu)^2/2\sigma^2\right]}$	σ and μ: continuous parameters $x > 0$
Weibull	$f(x) = \frac{\alpha}{\beta^{\alpha}} x^{\alpha-1} e^{-\left(x/\beta\right)^{\alpha}}$	α: continuous shape parameter β: continuous scale parameter $x \geq 0$ and $\alpha, \beta > 0$

conducted direct comparative analyses to evaluate agreement between the TP and AF measurements. A Bland–Altman analysis was applied to quantify systematic bias and the limits of agreement between the two tools for both tree height and crown diameter. This approach is particularly suitable for method comparison studies, as it provides a visual and statistical assessment of the consistency between paired measurements. The mean difference (BIAS) represents the average deviation between AF and TP, while the upper (ULOA) and lower (LLOA) limits of agreement correspond to BIAS ± 2×SD of the differences (Borz et al. 2024).

To complement the Bland–Altman analysis, we also calculated the mean absolute error (MAE) and root mean square error (RMSE) as summary indicators of overall accuracy and precision. These metrics quantify both systematic and random components of error, providing additional insight into the relative performance of the two tools. While the fitted probability density functions helped describe the general distributional patterns and variability of the data, the Bland–Altman analysis and associated error metrics offered a rigorous, pairwise evaluation of measurement agreement and accuracy between the AF and TP.

Results

To provide an overview of the tree measurements, descriptive statistics for tree height and crown diameter were calculated using data collected from both TP and AF. These statistics included the mean, median, standard deviation, kurtosis, skewness, and the range (minimum and maximum values).

The descriptive statistics indicate that the mean and median values for both height and crown diameter were very similar between the two tools (Table 2). The standard deviations for both variables also showed close agreement, suggesting comparable variability in the measurements. The range of the measurements (minimum and maximum) was nearly identical, with only minor differences observed.

For tree height, the mean and median values measured by AF and TP were very close (9.11 m vs. 9.15 m for the mean; 8.80 m vs. 9.10 m for the median). Both tools showed similar kurtosis (approximately 0.49) and skewness (close to 0), indicating a symmetric and slightly flat data distribution.

For crown diameter, both tools reported slightly right-skewed data with kurtosis values greater than 1, reflecting some outliers or large values in the dataset. The Rank column indicates the relative position of each observation in ascending order. The similar ranks for tree height (13 for both AF and TP) and crown diameter (27.40 for TP and 26.83 for AF) further illustrate the close agreement between the two tools. These results suggest that both AF and TP provide consistent measurements, with minimal variation in the central tendency or variability. The small differences in kurtosis and skewness highlight potential differences in how the tools handle extreme measurements, which will be further evaluated in subsequent analyses.

The parameter estimates for the five probability distributions (Gamma, Exponential, Normal, Log-Normal, and Weibull) were calculated for both tree height and crown diameter data measured using TP and AF (Table 3).

Table 2 Descriptive statistics of tree height and crown diameter measured with TruPulse 360B (TP) and Arboreal Forest app (AF). The 'Rank' column indicates the rank of each observation when sorted in ascending order.

Variable	Tool	Mean (m)	Median (m)	Std. Dev. (m)	Min (m)	Max (m)	Kurtosis	Skewness	Rank
Height (m)	TP	9.15	9.10	2.43	5.00	18.00	0.487	0.032	13.00
	AF	9.11	8.80	2.46	4.00	18.00	0.491	0.067	13.00
Crown Diameter (m)	TP	7.77	7.20	3.57	1.90	29.30	1.855	0.505	27.40
	AF	7.70	7.17	3.60	1.99	28.82	1.762	0.468	26.83

For the Gamma distribution, the α and β parameters were slightly lower for AF compared to TP for both variables, indicating comparable but slightly varied data dispersion. The Exponential distribution λ parameter was nearly identical between the two tools for both height and crown diameter, highlighting consistent overall trends in the measurements. The Normal distribution showed very close μ and σ values between AF and TP for both variables, reflecting strong agreement in central tendency and variability. Similarly, the Log-Normal distribution μ and σ parameters exhibited minimal differences between the tools, indicating consistent modeling of skewed data. The Weibull distribution parameters also aligned closely between AF and TP, with minor variations in the α and β parameters, particularly for crown diameter. These results suggest that both tools produce comparable data, allowing for effective modeling across all tested distributions.

The goodness-of-fit results for tree height and crown diameter data, measured using TP and AF, were evaluated using the KS and AD tests (Table 4). For both variables, the Normal and Weibull distributions consistently ranked as the best-fitting models, showing low KS and AD test statistics and high p-values, indicating a strong fit. The Gamma and Log-Normal distributions also provided reasonable fits, though they ranked slightly lower in performance. In contrast, the Exponential distribution performed poorly across both datasets, with significant deviations from the observed data (p-values < 0.001). The log-likelihood values further supported the superior performance of the Normal and Weibull distributions, particularly for crown diameter, where the Normal distribution ranked highest. Overall, the results demonstrated strong agreement between AF and TP measurements, with both tools achieving similar goodness-of-fit rankings across the tested distributions.

Figure 1 presents the frequency distributions and empirical cumulative distribution functions (CDFs) for tree height and crown diameter measurements obtained using TP and AF, with histograms illustrating observed and expected

Table 3 Parameter estimates for tree height and crown diameter distributions from TruPulse 360B (TP) and Arboreal Forest app (AF) measurements.

Variable	Distribution	Parameters (TP)	Parameters (AF)
Height (m)	Gamma	$\alpha = 14.36$, $\beta = 1.57$	$\alpha = 13.83$, $\beta = 1.52$
	Exponential	$\lambda = 0.109$	$\lambda = 0.110$
	Normal	$\mu = 9.15$, $\sigma = 2.42$	$\mu = 9.11$, $\sigma = 2.45$
	Log-Normal	$\mu = 2.17$, $\sigma = 0.267$	$\mu = 2.17$, $\sigma = 0.273$
	Weibull	$\alpha = 4.002$, $\beta = 10.072$	$\alpha = 3.93$, $\beta = 10.046$
Crown Diameter (m)	Gamma	$\alpha = 5.34$, $\beta = 0.687$	$\alpha = 5.17$, $\beta = 0.672$
	Exponential	$\lambda = 0.128$	$\lambda = 0.130$
	Normal	$\mu = 7.67$, $\sigma = 3.55$	$\mu = 7.69$, $\sigma = 3.59$
	Log-Normal	$\mu = 1.95$, $\sigma = 0.445$	$\mu = 1.94$, $\sigma = 0.451$
	Weibull	$\alpha = 2.26$, $\beta = 8.76$	$\alpha = 2.23$, $\beta = 8.98$

Table 4 Assessment of probability distribution fits for tree height and crown diameter distributions from TruPulse 360B (TP) and Arboreal Forest app (AF) measurements, showing Kolmogorov-Smirnov (KS) and Anderson-Darling (AD) statistics, p-values, and log-likelihood values (and their rank).

Variable	Distribution	KS Statistic	KS p-value	AD Statistic	AD p-value	Log-Likelihood (Rank)
Height (m)	Gamma	0.0559	0.511	0.364	0.883	-493.28 (4th)
	Exponential	0.413	<0.001	53.49	<0.001	-701.25 (-)
	Normal	0.064	0.335	0.887	0.422	-498.45 (2nd)
	Log-Normal	0.0723	0.210	0.559	0.687	-494.32 (3rd)
	Weibull	0.0643	0.335	1.286	0.237	-506.64 (1st)
Crown Diameter (m)	Gamma	0.0549	0.792	0.283	0.949	-359.71 (3rd)
	Exponential	0.315	<0.001	21.98	<0.001	-431.39 (-)
	Normal	0.088	0.227	1.698	0.135	-383.53 (1st)
	Log-Normal	0.0612	0.669	0.557	0.688	-359.61 (4th)
	Weibull	0.789	0.347	1.327	0.223	-376.53 (2nd)

measurements overlaid with fitted probability distributions (Weibull, Normal, Log-Normal, and Gamma). The top row displays tree height distributions, where TP (A) represents expected height and AF (B) represents observed height, while the bottom row presents crown diameter distributions, with TP (C) showing expected values and AF (D) showing observed values.

The empirical CDFs for both methods align closely with the fitted distributions, particularly Weibull and Log-Normal, indicating a strong representation of the data. However, the histogram for TP exhibits a wider spread than AF, suggesting greater variability in height measurements, whereas AF height distribution appears slightly left-skewed, indicating a tendency to underestimate taller trees. Similarly, for crown diameter, Weibull and Log-Normal provide the best fit, while Normal and Gamma show deviations. TP measurements display a broader range of crown diameters, whereas AF measurements are more concentrated around the mean, possibly underestimating extreme values.

The overall goodness-of-fit analysis confirms that Log-Normal and Weibull distributions provide the most suitable models, closely following the empirical data, while Normal and Gamma struggle to capture the distribution tails, particularly for AF measurements. This visual comparison highlights the differences between the two measurement methods, with TP exhibiting greater variability and AF producing more concentrated estimates.

These findings reinforce the statistical goodness-of-fit analysis in Tables 3 and 4, further supporting the selection of Log-Normal and Weibull distributions for modeling tree height and crown diameter data.

Figure 2 presents the probability-probability (P-P) plots for tree height and crown diameter measurements obtained using TP and AF, assessing the goodness-of-fit by comparing empirical probabilities with theoretical probabilities from Weibull, Normal, Log-Normal, and Gamma distributions. Ideally, a perfect fit would result in points aligning along the diagonal reference line (y = x), with deviations indicating discrepancies between observed and theoretical distributions.

For tree height (top row), the Weibull and Log-Normal distributions exhibit the best alignment for both measurement methods, confirming their suitability for modeling height data. However, the Normal and Gamma distributions show noticeable deviations, particularly at the probability extremes, suggesting difficulty in capturing distribution tails. The AF P-P plot displays slightly greater spread at the extremes compared to TP, indicating potential variability or bias in AF height estimations. Similarly, for crown diameter (bottom row),

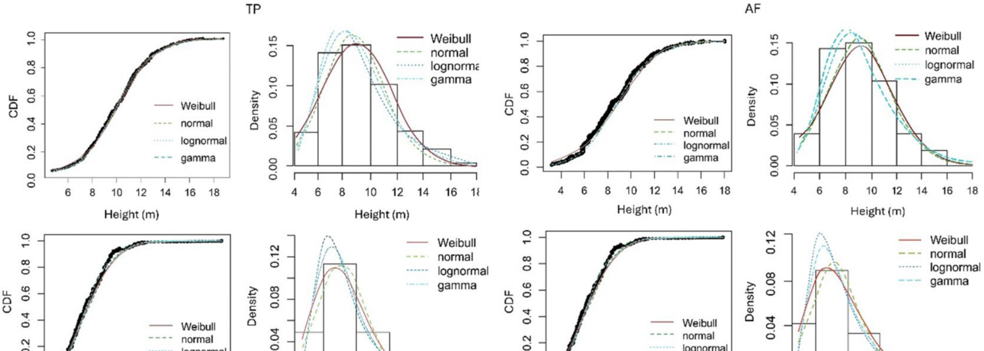


Figure 2 Cumulative Distribution Functions (CDFs) and Probability Density Functions (PDFs) for tree height and crown diameter from TruPulse 360B (TP) and Arboreal Forest app (AF).

Weibull and Log-Normal distributions provide the closest fit, while Gamma and Normal exhibit minor deviations, particularly in mid-range probability values. Notably, AF crown diameter estimates show a slightly tighter fit along the diagonal compared to its height estimates, suggesting better consistency in measuring crown diameter.

Overall, Weibull and Log-Normal emerge as the most appropriate distributions for both height and crown diameter, reinforcing the patterns observed in Figure 1. AF demonstrates slightly greater deviations in height estimates, potentially leading to under- or over-estimations for extreme values, whereas its crown diameter measurements align closely with TP. These findings further validate the use of Weibull and Log-Normal distributions for tree height and crown diameter modeling, supporting the statistical conclusions drawn in Tables 3 and 4.

The Bland–Altman and error analysis results (Figure 3) revealed a high level of agreement between the AF and the TP for tree height measurements, with a mean bias of −0.01 m, indicating that AF slightly underestimated height relative to TP. The MAE and RMSE were 0.125 m and 0.211 m, respectively, demonstrating strong consistency and low deviation between the two methods. The limits of agreement ranged from −0.43 m to 0.41 m, suggesting that 95% of the measurement differences fell within this narrow interval.

For crown diameter, the bias was −0.59 m, showing a tendency of AF to underestimate this parameter compared with TP. The corresponding MAE and RMSE values were 2.02 m and 2.70 m, respectively, with limits of agreement between −5.89 m and 4.70 m. These wider limits indicate greater variability in crown diameter estimations than in height measurements.

Overall, the results demonstrate that while AF provided highly comparable height measurements to the professional laser rangefinder, greater discrepancies were observed for crown diameter, likely due to the challenges of visually delineating crown edges in the field using AF.

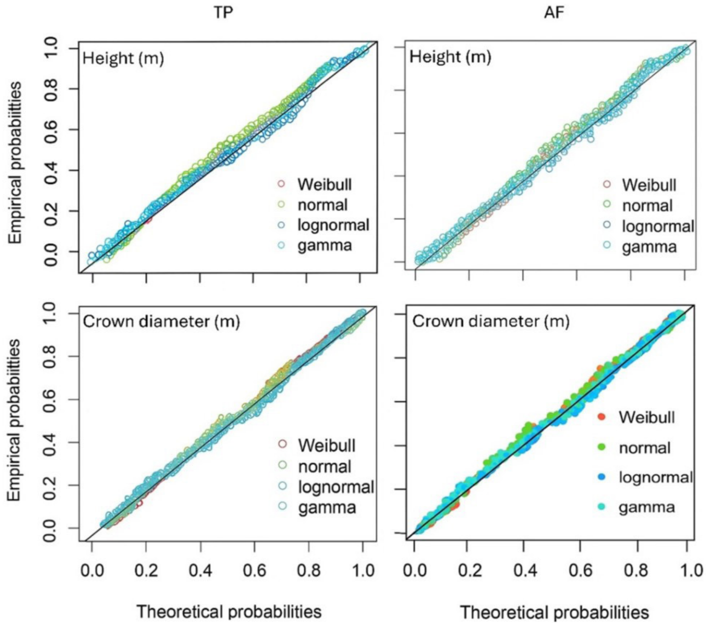


Figure 3 P-P plots for tree height and crown diameter measurements from TruPulse 360B (TP) and Arboreal Forest app (AF), comparing empirical and theoretical probabilities. Weibull and Log-Normal distributions show the best fit, while Normal and Gamma exhibit deviations, especially at probability extremes.

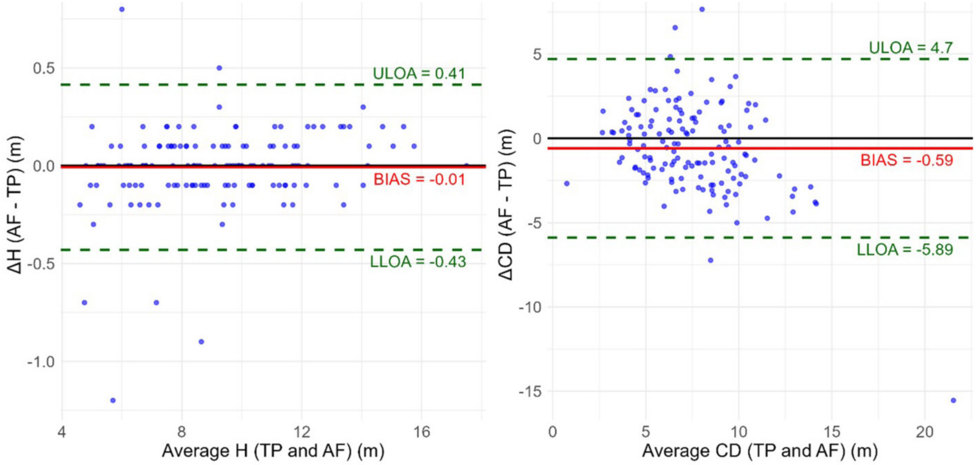


Figure 4 Bland–Altman plots showing the agreement between TruPulse 360B (TP) and Arboreal Forest app (AF) for tree height (H) and crown diameter (CD). ΔH and ΔCD represent the differences between AF and TP measurements. BIAS – mean of the differences, ULOA – upper limit of agreement (BIAS + 2×SD), LLOA – lower limit of agreement (BIAS − 2×SD). Black solid line – identity line (zero difference), red solid line – bias, green dashed lines – limits of agreement.

Discussions

Comparing AF, based on ARKit 6, with TP provides an opportunity to explore the potential of general-purpose AR in forestry, highlighting how AR technology could potentially replace specialized tools like the TP, whose efficiency has been verified in previous studies (Panagiotidis et al. 2016; Sadeghian et al. 2022).

ARKit 6 offers flexibility for innovative apps such AF that could combine tree measurements with other data, while TP provides precision for forestry tasks. This comparison is more forward-looking, focusing on how AR technology might transform forestry in the future, unlike the more current-focused comparison between specific applications (e.g., Arboreal Forest, ForestScanner, 3D Scanner, TRESTIMA^{TM}) and tools such as diameter tape (Tatsumi et al. 2023) and caliper (Vastaranta et al. 2015; Gollob et al. 2021; Wang et al. 2022; Howie & De Stefano 2024). Additionally, by comparing two LiDAR-based tools, this study provides insight into how consumer-grade LiDAR in ARKit 6 compares to professional-grade laser measurement devices, offering a clearer picture of AR current limitations and future potential.

While previous studies primarily assessed AR-based forestry measurements through DBH estimation (e.g., Wang et al. 2022; Gülci et al. 2023; Tatsumi et al. 2023; Howie & De Stefano 2024; Su et al. 2024), this study serves as a complementary investigation by focusing on tree height and crown attributes. These variables are critical for evaluating forest structure, biomass estimation, and growth modeling, yet they have received less attention in AR-based forestry research.

By extending AR application beyond DBH, this study broadens the understanding of AR technology capabilities, demonstrating its potential for capturing a more comprehensive set of tree attributes. Since height and crown dimensions are often more challenging to measure accurately in the field, this research helps determine whether AR can offer a viable cost-efficient alternative to professional-grade laser tools (i.e., TP) for these measurements.

The findings extend the scope of previous AR studies, bridging the gap between DBH-focused research and the need for more comprehensive forest inventory methods.

Most previous studies evaluating AR-based forestry measurements have relied on agreement analysis and error metrics to compare AR with traditional tools (e.g., Vastaranta et al. 2015; Molinier et al. 2016; Song et al. 2023; Howie & De Stefano 2024). While these methods provide valuable insights into measurement accuracy, they often focus on direct pairwise comparisons, which may overlook broader distributional patterns and variability. In line with a few recent studies (e.g., Ahamed et al. 2023; Su et al. 2024), this study complements prior research by introducing PDFs and CDFs as an alternative approach to assessing measurement efficiency.

By fitting statistical distributions to measurement data, this study allows for a more nuanced evaluation of accuracy and precision, revealing how different tools handle variability, extreme values, and overall data trends. The results demonstrate that AF and TP produce comparable measurement distributions, reinforcing AR potential as a reliable alternative for forestry applications. This distribution-based approach, combined with conventional error analyses, enhances the robustness of AR evaluations and offers a more in-depth statistical framework for future studies comparing forestry measurement tools.

The descriptive statistics indicate a high level of agreement between AF and TP for both tree height and crown diameter measurements across a diverse mix of broadleaved and coniferous species. For tree height, the near-identical values in kurtosis, skewness and rank (Table 2) suggest that both tools produce a symmetric, slightly platykurtic distribution, meaning the data is relatively evenly spread without extreme peaks. This consistency suggests that AF is not prone to systematic over- or underestimation of tree height, at least in the sampled trees.

For crown diameter, both tools show right-skewed distributions with kurtosis values exceeding 1, indicating the presence of some outliers or larger-than-expected values. While the measurements remain closely aligned, the slight differences in kurtosis and skewness (Table 2) suggest that the two tools may handle extreme values differently. This could be due to differences in measurement techniques, AF may be more sensitive to variations in crown shape or user interpretation, whereas TP laser-based approach might be more stable for irregular canopy structures. Overall, these findings suggest that ARKit 6, despite being a consumer-grade tool, and AF are capable of producing tree height and crown diameter measurements comparable to those from TP.

However, the small differences in statistical distribution indicate that further analysis is necessary to assess measurement precision and reliability in greater depth. While this study utilized the Arboreal Forest application, as verified by Howie and De Stefano (2024), it is important to consider how other AR-based applications might perform under similar conditions. Future research could explore the potential variations in height and crown measurement outcomes across different apps such as TreeHeight (Shen et al. 2023), TRESTIMA^{TM} (Vastaranta et al. 2015), and Working Trees (Ahamed et al. 2023), ForestScanner (Tatsumi et al. 2023) in addition to Arboreal Forest; various tree species, stand conditions, and measurement scenarios, contributing to a broader understanding of AR applicability in forestry.

The similarity in distribution parameters (Table 3) suggests that AF produces measurement patterns that closely resemble those obtained from TP, highlighting its potential as a reliable alternative in forestry applications. This approach of using probability distributions to explore measurement differences aligns with previous studies, such as Ahamed et al. (2023) and Su et al. (2024), who applied PDFs to compare field measurements and AR-based estimations of DBH.

For the Gamma distribution, the α and β parameters were slightly lower for AF, indicating a similar but marginally more dispersed dataset compared to TP. This suggests that while both tools capture similar measurement trends, AF might introduce slightly more variability. The Exponential distribution λ parameter showed nearly identical values between the two tools, further supporting the consistency of overall measurement trends. The Normal distribution parameters (μ and σ) displayed minimal differences, confirming that both tools exhibit similar central tendency and variability. Likewise, the Log-Normal distribution parameters aligned closely, indicating that both tools effectively model the natural skewness present in tree height and crown diameter data. The Weibull distribution, often used in forestry for modeling tree size distributions, also demonstrated strong agreement between the two tools, with only minor differences in its α and β parameters, particularly for crown diameter. These results indicate that AF can generate measurements that align well with those from an advanced field tool like TP, even when analyzed through different statistical distributions.

The slight variations in parameter estimates, particularly in the Gamma and Weibull distributions, suggest that AF may introduce marginally different dispersion patterns, which warrants further exploration in terms of measurement precision under varying conditions.

While goodness-of-fit analysis was based on a sample size of 215 trees (Table 4), which is relatively robust for goodness-of-fit testing, it is important to note that smaller sample sizes could lead to less reliable conclusions, as seen in studies such as Song et al. (2023) with 22 trees, and Wang et al. (2022) with 50 trees. Conversely, studies with larger sample sizes, such as Tatsumi et al. (2023) with 672 trees and Ahamed et al. (2023) with 414 trees, provide more robust evidence in similar applications. Despite this, the results of this study highlight a strong agreement between AF and TP measurements, as both tools exhibited similar goodness-of-fit rankings across all tested probability distributions. The fact that AF measurement patterns align well with TP in terms of distributional fit suggests that AF provides reliable data consistency, making it a promising alternative for forestry applications.

The goodness-of-fit analysis (Tables 3 and 4) is verified by the visual analysis of PDFs and CDFs (Fig. 1), confirming that Normal and Gamma distributions struggle to capture the tails of the data, particularly for AF measurements. This suggests that AF using ARKit 6 mobile LiDAR technology produces more constrained estimates, whereas TP reflects greater natural variation in tree attributes. These insights are crucial for forestry applications, as they help practitioners understand the limitations and strengths of AR-based tools in different measurement contexts.

Previous studies have also employed PDFs to compare field and AR-based measurements. Ahamed et al. (2023) used a PDF to compare field and AR-based DBH measurements, but they did not specify which PDF was used, leaving a gap in understanding the distribution suitability. Similarly, Su et al. (2024) applied a PDF to compare field and AR-based DBH and height measurements, without mentioning the specific PDF employed. These studies highlight the value of using PDFs for such comparisons, but also emphasize the limitation in the lack of clarity regarding the chosen distribution, which can affect the robustness of their findings. Overall, the combination of statistical and visual analyses provides a comprehensive evaluation of AR performance.

The P-P plots in Figure 2 provide a detailed assessment of the goodness-of-fit between observed tree measurements and theoretical probability distributions. Ideally, a strong model fit would result in data points closely following the diagonal reference line ($y = x$), with deviations indicating potential mismatches between observed and theoretical distributions.

For tree height, the Weibull and Log-Normal distributions exhibit the best alignment for both TP and AF, confirming their suitability for height modeling. In contrast, Normal and Gamma distributions show noticeable deviations, particularly at the probability extremes, indicating difficulties in capturing the tails of the data distribution. This suggests that while Normal and Gamma distributions may adequately describe central tendencies, they fail to represent the variability observed in field measurements. Additionally, AF P-P plot displays slightly greater spread at the extremes compared to TP, suggesting potential measurement bias or variability in ARKit-based estimation of taller trees.

For crown diameter, a similar pattern emerges. Weibull and Log-Normal distributions provide the closest fit, whereas Gamma and Normal distributions exhibit deviations, particularly in mid-range probability values. Interestingly, AF crown diameter measurements align more closely with TP compared to its height estimates, suggesting that AF performs more consistently in measuring crown diameter than height. This could be due to differences in how the AR-based system captures vertical vs. horizontal dimensions, with height estimates potentially being more sensitive to variations in tree structure and environmental factors. Overall, these findings are in accordance with the previous results from Figure 1 and the statistical analyses in Tables 3 and 4, confirming that Weibull and Log-Normal distributions are the most suitable models for both tree height and crown diameter.

The slightly larger deviations in AF height estimates suggest the need for further calibration or algorithmic refinement, especially when measuring taller trees. Meanwhile, its strong agreement in crown diameter measurements highlights its potential for practical forestry applications. These insights contribute to a deeper understanding of AR-based measurement tools, guiding their future improvements and applications in forest inventory and ecological studies.

The Bland–Altman and error-based analyses further support the strong agreement between the tools, while also revealing subtle differences in measurement behavior. The minimal bias in height estimates suggests that AF can reliably capture vertical dimensions, likely because height measurements depend primarily on stable vertical alignment and range detection, which are handled effectively by the device LiDAR sensor. In contrast, the slightly higher variability observed for crown diameter may result from the greater complexity of capturing horizontal tree structures, where irregular canopy shapes, overlapping branches, and user positioning can introduce additional measurement uncertainty.

These trends are consistent with previous findings (e.g., Borz et al. 2024), which indicate that AR-based forestry measurements tend to be more sensitive to object geometry and user interpretation than to environmental conditions. Overall, the analysis suggests that while AF is highly reliable for tree height estimation, further refinement of its algorithms and scanning methods could improve accuracy for crown dimensions, enhancing its potential as a cost-effective alternative to professional-grade laser instruments.

Conclusions

This study focused on comparing a consumer-grade tool (i.e., AF, based on ARKit 6, a general-purpose AR-based tool) with TP, a professional-grade laser device, to explore the potential of AR technology in forestry applications. By concentrating on tree height and crown diameter measurements across a diverse mix of broadleaved and coniferous species, we evaluated how AR could potentially disrupt established tools like the TP.

The findings suggest that ARKit 6, despite being a consumer-grade tool, and AF can provide measurements comparable to TP, demonstrating the flexibility and potential of AR in forestry.

Our analysis goes beyond the direct comparison of measurement tools, shifting the focus toward how AR technology might transform forestry practices in the future. AF, with its capacity for real-time data integration and app innovation, presents a promising alternative to specialized forestry equipment like TP. As AR technology advances, its role in forestry could expand beyond basic measurements, enabling more complex tasks such as modeling, automation, and data integration, bridging the gap between traditional field measurements and high-tech solutions.

This research also fills a gap in AR-based forestry measurement studies by exploring tree height and crown attributes, which have received less attention compared to DBH estimation. By extending the application of AR beyond DBH, we offer a more comprehensive understanding of AR potential in forest inventory methods. The use of PDFs and CDFs for measurement comparison adds depth to the analysis, revealing that Weibull and Log-Normal distributions best describe the data. Bland-Altman analysis and error metrics further confirmed strong agreement between AF and TP, particularly for height measurements, with slightly greater variability observed for crown diameter.

The findings indicate strong agreement between the two tools, highlighting ARKit 6 and AF reliability and potential as a forestry tool. Furthermore, the use of robust statistical methods, such as goodness-of-fit tests and distribution analysis, provides a reliable evaluation of AF performance, ensuring that comparisons between AR and modern tools go beyond simple error metrics.

This study demonstrates that AR technology is not only a viable alternative to professional-grade laser tools but may, in some cases, offer a more accessible and versatile solution for forestry measurement. In conclusion, as AR technology evolves, its application in forestry is likely to expand and improve. This study contributes to the growing body of knowledge by assessing AR potential alongside TP, suggesting that AR tools can serve as effective, cost-efficient alternatives for various forestry measurement tasks. Future research could further explore the integration of AR in forest inventory methods and evaluate the performance of other AR applications under varying field conditions.

Conflict of interest

The authors declare that they have no conflict of interest.

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References

Ahamed A., Foye J., Poudel S., Trieschman E., Fike J., 2023. Measuring tree diameter with photogrammetry using mobile phone cameras. Forests 14(10): 2027. https://doi.org/10.3390/f14102027.

Atkins J.W., Bhatt P., Carrasco L., Francis E., Garabedian J. E., Hakkenberg C. R., Hardiman B.S., Jung J., Koirala A., et al., 2023. Integrating forest structural diversity measurement into ecological research. Ecosphere 14(9): e4633. https://doi.org/10.1002/ecs2.4633.

Borz S.A., Morocho Toaza J.M., Forkuo G.O., Marcu M.V., 2022. Potential of Measure App in estimating log biometrics: A comparison with conventional log measurement. Forests 13(7): 1028. https://doi.org/10.3390/f13071028.

Borz S.A., Morocho Toaza J.M., Proto A.R., 2024. Accuracy of two LiDAR-based augmented reality apps in breast height diameter measurement. Ecological Informatics 81: 102550. https://doi.org/10.1016/j.ecoinf.2024.102550.

Celes C.H.S., de Araujo R.F., Emmert F., Lima A.J.N., Campos M.A.A., 2019. Digital approach for measuring tree diameters in the Amazon forest. Floresta e Ambiente 26: e20160384. https://doi.org/10.1590/2179-8087.038416.

Chioni C., Maragno A., Pianegonda A., Ciolli M., Favargiotti S., Massari G.A., 2023. Low-cost 3D virtual and dynamic reconstruction approach for urban forests: The Mesiano University Park. Sustainability 15(19): 14072. https://doi.org/10.3390/su151914072.

Clark N.A., Wynne R.H., Schmoldt D.L., 1999. A review of past research on dendrometers. Forest Science 46(4): 570-576. https://doi.org/10.1093/forestscience/46.4.570.

Coops N.C., Tompalski P., Goodbody T.R.H., Queinnec M., Luther J.E., Bolton D.K., White J.C., Wulder M.A., van Lier O.R., Hermosilla T., 2021. Modelling lidar-derived estimates of forest attributes over space and time: A review of approaches and future trends. Remote Sensing of Environment 260: 112477. https://doi.org/10.1016/j.rse.2021.112477.

Dalla Corte A.P., Souza D.V., Rex F.E., Sanquetta C.R., Mohan M., Silva C.A., Almeyda Zambrano A.M., Prata G., Alves de Almeida D.R., et al., 2020. Forest inventory with high-density UAV-Lidar: Machine learning approaches for predicting individual tree attributes. Computers and Electronics in Agriculture 168: 105815. https://doi.org/10.1016/j.compag.2020.105815.

Erfanifard Y., Sheikholeslami N., 2017. Competitive interactions of Persian oak coppice trees (*Quercus brantii* var. *persica*) in a pure dry woodland revealed through point pattern analysis. Folia Geobotanica 52(2): 113-127. https://doi.org/10.1007/s12224-017-9280-3.

Ferrara C., Puletti N., Guasti M., Scotti R., 2023. Mapping understory vegetation density in Mediterranean forests: Insights from airborne and terrestrial laser scanning integration. Sensors 23(1): 511. https://doi.org/10.3390/s23010511.

Follett M., Nock C.A., Buteau C., Messier C., 2016. Testing a new approach to quantify growth responses to pruning among three temperate tree species. Arboriculture & Urban Forestry 42(3): 133-145. https://doi.org/10.48044/jauf.2016.012.

Gollob C., Ritter T., Kraßnitzer R., Tockner A., Nothdurft A., 2021. Measurement of forest inventory parameters with Apple iPad Pro and integrated LiDAR technology. Remote Sensing 13(15): 3129. https://doi.org/10.3390/rs13163129

Gorgoso-Varela J.J., Adedapo S.M., Ogana F.N., 2024. A comparison of probability density functions fitted by moments and maximum likelihood estimation methods used for diameter distribution estimation. Forests, 15(3), 425. https://doi.org/10.3390/f15030425.

Gülci S., Yurtseven H., Akay A.O., Akgul M., 2023. Measuring tree diameter using a LiDAR-equipped smartphone: A comparison of smartphone- and caliper-based DBH. Environmental Monitoring and Assessment 195: 678. https://doi.org/10.1007/s10661-023-11366-8.

Howie N.A., De Stefano A., 2024. Measuring tree diameter using LiDAR equipped iPad: An evaluation of ForestScanner and Arboreal Forest applications. Forest Science 70(4): 304-310. https://doi.org/10.1093/forsci/fxae017.

Liang X., Kankare V., Hyyppä J., Wang Y., Kukko A., Haggrén H., Yu X., Kaartinen H., Jaakkola A., et al., 2016. Terrestrial laser scanning in forest inventories. ISPRS Journal of Photogrammetry and Remote Sensing 115: 63-77. https://doi.org/10.1016/j.isprsjprs.2016.01.006.

Liu C., Zhang S.Y., Lei Y., Newton P.F., Zhang L., 2004. Evaluation of three methods for predicting diameter distributions of black spruce (Picea mariana) plantations in central Canada. Canadian Journal of Forest Research 34(12): 2424–2432. https://doi.org/10.1139/X04-117.

Luetzenburg G., Kroon A., Bjørk A.A., 2021. Evaluation of the Apple iPhone 12 Pro LiDAR for an Application in Geosciences. Scientific Reports 11: 22221. https://doi.org/10.1038/s41598-021-01763-9.

Luoma V., Saarinen N., Wulder M.A., White J.C., 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.

Magnuson R., Erfanifard Y., Kulicki M., Gasica T.A., Tangwa E., Mielcarek M., Sterenczak K., 2024. Mobile devices in forest mensuration: A review of technologies and methods in single tree measurements. Remote Sensing 16: 3570. https://doi.org/10.3390/rs16193570.

Molinier M., López-Sánchez C.A., Toivanen T., Korpela I., Corral-Rivas J.J., Tergujeff R., Häme T., 2016. Relasphone—Mobile and participative in situ forest biomass measurements supporting satellite image mapping. Remote Sensing 8(10): 869. https://doi.org/10.3390/rs8100869.

Panagiotidis D., Abdollahnejad A., Surový P., Chiteculo V., 2016. Determining tree height and crown diameter from high-resolution UAV imagery. International Journal of Remote Sensing 37(24): 5831-5852. https://doi.org/10.1080/01431161.2016.1264028.

Sadeghian H., Naghavi H., Maleknia R., Soosani J., Pfeifer N., 2022. Estimating the attributes of urban trees using terrestrial photogrammetry. Environmental Monitoring and Assessment 194: 625. https://doi.org/10.1007/s10661-022-10294-3.

Sandim A., Amaro M., Silva M.E., Cunha J., Morais S., Marques A., Ferreira A., Lousada J. L., Fonseca T., 2023. New technologies for expedited forest inventory using smartphone applications. Forests 14(8): 1553. https://doi.org/10.3390/f14081553.

Shen Y., Huang R., Hua B., Pan Y., Mei Y., Dong M., 2023. Automatic tree height measurement based on three-dimensional reconstruction using smartphone. Sensors 23(1): 7248. https://doi.org/10.3390/s230107248.

Song J., Huang Q., Zhao Y., Song W., Fan Y., Lu C., 2023. Automatic extraction of forest inventory variables at the tree level by using smartphone images to construct a three-dimensional model. Forests 14(6): 1081. https://doi.org/10.3390/f14061081.

Su J., Fan Y., Mannan A., Wang S., Long L., Feng Z., 2024. Real-time estimation of tree position, tree height, and tree diameter at breast height point, using smartphones based on monocular SLAM. Forests 15: 939. https://doi.org/10.3390/f15060939.

Su Y., Wu Z., Zheng X., Qiu Y., Ma Z., Ren Y., Bai Y., 2025. Harmonizing remote sensing and ground data for forest aboveground biomass estimation. Ecological Informatics 86: 103002. https://doi.org/10.1016/j.ecoinf.2025.103002.

Tatsumi S., Yamaguchi K., Furuya N., 2023. ForestScanner: A mobile application for measuring and mapping trees with LiDAR-equipped iPhone and iPad. Methods in Ecology and Evolution 14(10): 1603-1609. https://doi.org/10.1111/2041-210X.14072.

Vastaranta M., Latorre E.G., Luoma V., Saarinen N., Holopainen M., Hyyppä J., 2015. Evaluation of a smartphone app for forest sample plot measurements. Forests 6(4): 1179-1194. https://doi.org/10.3390/f6041179.

Wang F., Heenkenda M.K., Freeburn J.T., 2022. Estimating tree Diameter at Breast Height (DBH) using an iPad Pro LiDAR sensor. Remote Sensing Letters 13(6): 568-578. https://doi.org/10.1080/2150704X.2022.2051635.

Yang M., Zhou X., Peng C., Li T., Chen K., Liu Z., Li P., Zhang C., Tang J., Zou Z., 2023. Developing allometric equations to estimate forest biomass for tree species categories based on phylogenetic relationships. Forest Ecosystems 10: 100130. https://doi.org/10.1016/j.fecs.2023.100130.

Zhao Y., Im J., Zhen Z., Zhao Y., 2023. Towards accurate individual tree parameters estimation in dense forest: optimized coarse-to-fine algorithms for registering UAV and terrestrial LiDAR data. GIScience & Remote Sensing 60(1): 2197281. https://doi.org/10.1080/15481603.2023.2197281.