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RESEARCH

Measuring tree diameter using a LiDAR-equipped smartphone: a comparison of smartphone- and caliper-based DBH

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Abstract Tree diameter measurement is one of the most important stages of forest inventories to assess growing stock, aboveground biomass, and landscape restoration options, among others. This study investigates the accuracy of measuring tree diameters using a Light Detection and Ranging (LiDAR)–equipped smartphone vs. a normal caliper (reference data) and the opportunity to use low-cost smartphone-based applications in forest inventories. To estimate the diameter at breast height (DBH) of single trees, we used a smartphone with a third-party app that automatically analyzed three-dimensional (3D) point clouds. For two different measurement techniques, we compared the two measurement techniques based on DBH data from 55 Calabrian pine (*Pinus brutia* Ten.) and 50 oriental plane (*Platanus orientalis* L.) trees using the paired-sample *t*-test and Wilcoxon signed-rank test. Mean absolute error (MAE), mean squared error (MSE), root mean square error (RMSE), percent bias (PBIAS), and coefficient of determination (R^2) were used as precision and error statistics. Statistical differences were observed between the reference and smartphone-based DBH according to the paired-sample *t*-test and Wilcoxon signed-rank test. The R^2 values obtained were determined as 0.91, 0.88, and 0.88 for Calabrian pine, oriental plane, and all tree species (105 trees), respectively. In addition to the overall accuracy performance of the comparison between reference and estimations, MAE, MSE, RMSE, and PBIAS values for the DBH of 105 tree stems were calculated as 1.56 cm, 5.42 cm, 2.33 cm, and −5.10%, respectively. The estimation accuracies increased in regular stem forms compared with forked stems particularly observed on plane trees. Further experiments are needed to investigate the uncertainties associated with trees of different stem forms, species (coniferous or deciduous), different work environments, and different types of LiDAR and LiDAR-based app scanners.

Keywords Precision forestry · Individual tree measurement · Vision technology · Close-range detection · Accuracy assessment

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Introduction

Forests may face alteration, degradation, or fragmentation of their natural habitat due to poor planning or global climate change (Hansen et al., 2001). Forest planning with ecological, economic, and social aspects plays a vital role in sustainable management. Therefore, continuous observations and assessment of forest inventory parameters are necessary to reduce negative impacts on forests (Zhao et al., 2014). The diameter of breast height (DBH) is one of the fundamental parameters to estimate/calculate forest inventory parameters due to high correlations with tree height, tree volume, and biomass (Wang et al., 2021). Traditionally, in practice, DBH measurements are made by a diameter tape (d-tape) or caliper and by assuming a circular-shaped cross-section (Tischendorf, 1943). Diameter tapes are commonly used to monitor permanent sample plots for repeated measurements (Binot et al., 1995; Liu et al., 2011). Calipers are measurement devices, which are faster and easier for measuring large forested areas. However, due to the irregular shape of trees, too many errors can occur in the calipers (Moran & Williams, 2002). In forest engineering studies, traditional instruments such as dendrometers are still performed using manual instruments (i.e., diameter rulers and calipers) because of accuracy, precision, cost, and simplicity of operation. Although there are newly introduced technical instruments, low-cost and labor-intensive mechanical or semi-electronic calipers are typically used to measure the diameter of individual trees (Clark et al., 2000). However, the researchers have delved into the combination of terrestrial inventories and modern sensors (low-cost consumer-grade instruments such as cameras and Light Detection and Ranging (LiDAR)) to obtain more accurate tree positions and accurate stem measurements, reducing labor intensity, saving time, and reducing training skills (Gollob et al., 2021; McGlade et al., 2022; Pace et al., 2022).

Accuracy and precision are two important concepts in the field of measurement and data analysis. In summary, precision is about consistency and reproducibility, while accuracy is about correctness and proximity to the true or target value. Both precision and accuracy are important in scientific and technical measurements, and a good measurement should be both precise and accurate. With the development of technology, new remote sensing (RS) and precision technology/techniques have become powerful integrated tools for forest inventory parameters and tree stem measurement (Drew & Downes, 2009; Liang et al., 2014b; White et al., 2016). To sustain high benefits from forest resources and proper planning of forests, precision forestry should be considered in forest inventory works. Precision forestry uses precision technology, which can be summarized as RS, digital surveying equipment, high-tech forestry vehicles, geographical information systems, specific software and hardware, and so on (Kovácsová & Antalová, 2010). Remote measurement and detection methods are being investigated, particularly for single tree stem diameter measurements (Iglhaut et al., 2019; Xu et al., 2021). The methods can be divided into two categories, which can be divided into LiDAR and structure-in-motion (SfM) photogrammetry-based methods (Balenović et al., 2020; Gao & Kan, 2022; Hyyppä et al., 2017; Liang, et al., 2014a; Surový et al., 2016). Over the last several decades, many studies have used different LiDAR systems for the measurement of tree parameters such as DBH and tree and crown height. LiDAR systems have used terrestrial laser scanners (Akgül et al., 2016; Heinzel & Huber, 2017; Liu et al., 2018; Shimizu et al., 2022; Trochta et al., 2017; Vauhkonen et al., 2012; Yurtseven et al., 2019b), handheld laser scanning (Fan et al., 2021; Vatandaşlar & Zeybek, 2020; Zhou et al., 2019), and airborne laser scanners (Giannetti et al., 2018; Zhang et al., 2020). Additionally, it is seen that unmanned aerial vehicle (UAV) systems are used in similar studies to measure tree parameters (Bruggisser et al., 2020; Wieser et al., 2017; Yurtseven et al., 2019a). Although these laser scanner-based terrestrial or aerial systems provide positive/significant results, they are still very expensive and therefore unsuitable for general use (Gusmão et al., 2020). Also, data processing is a time-consuming and labor-intensive process to obtain ultimate data.

Recently, new alternative measurement techniques have emerged due to innovation brought by smartphones and tablets through new sensors and apps. In 2020, Apple introduced smartphones with LiDAR sensors in certain iPhone and iPad models. Compared to other professional LiDAR equipment, lighter (> 189 g) and lower-cost (> 899 Euro) consumer-grade LiDAR-equipped smartphones and tablets are preferred to increase efficiency in low-cost fieldwork.

Additionally, newly developed third-party software such as the ForestScanner app provides real-time DBH measurement, and the location of an individual tree was introduced at the end of 2021. The present literature includes studies that use smartphone apps to perform different DBH measurements. In this context, Ucar et al. (2022) evaluated the accuracy of direct and indirect measurements of the DBH using calipers and a smartphone with a free-of-charge app for three different tree species (oak, pine, and poplar) at different distances. Fan et al. (2018) used the RGB-D simultaneous localization and mapping (SLAM) smartphone app to perform DBH measurements, which were then compared to the measurement tape method to ensure accuracy. In another study performed by Vastaranta et al. (2015), DBH measurements were taken in different areas using the TRESTIMA smartphone app, and these measurements were compared with caliper measurements. Celes et al. (2019) investigated direct and indirect methods for measuring trees with DBH > 40 cm using images captured by smartphone cameras and a consumer-grade camera. Gollob et al. (2021) evaluated a LiDAR-equipped iPad tablet to estimate DBH with the best root mean square error (RMSE) result of 3.13 cm. Kędra and Barbeito (2022) conducted a comparative study of the DBH measurements of Norway spruce, and they found a mean absolute error (MAE) value of 0.84 cm using smartphone (LG LM-K410EMW)-based single-image photogrammetry and measurement tape techniques. On the other hand, Marzulli et al. (2020) developed an automatic method to extract the stems from the dense point cloud–derived cylindrical models using a smartphone (RMSE = 1.9 cm) for DBH measurements in terms of Aleppo pine tree and cypress tree species. In previous studies, the accuracy of DBH measurements was evaluated for different tree species, different smartphone applications, and photogrammetry techniques. In this study, an iPhone 13 Pro Max with a third-party app installed that automatically analyzes three-dimensional (3D) point clouds was used along with a time-of-flight LiDAR sensor and a fully convolutional neural network model.

This study aimed to obtain DBH values of Calabrian pine (*Pinus brutia* Ten.) and oriental plane (*Platanus orientalis* L.) tree species using an iPhone Operating System (iOS)–based smartphone app. Then, the results with the reference values obtained from the caliper were compared and evaluated in accordance with the accuracy. Accordingly, the diameter of individual tree stems at a breast height was estimated with the support of consumer-grade LiDAR-assisted augmented reality (AR) technology on a smartphone. The measurement results of a normal caliper and the real-time estimated diameters with a smartphone were compared statistically and technically.

Materials and methods

According to our study objectives, an application workflow is created (Fig. 1). Within the scope of the created workflow, the plan is to make simultaneous DBH measurements in the field using a caliper and state-of-the-art smartphone LiDAR system. First, the forest area where the prepared workflow can be applied and controlled measurements can be carried out has been determined. It was evaluated that the selection of a forest area with deciduous and coniferous trees together would be more suitable for the study purposes.

Study area

The study area was on the Kahramanmaras Sutcu Imam University campus in the eastern Mediterranean region of Turkey, which is located at 37° 35′ 06″ N and 36° 48′ 21″ E. The main study area with a mean altitude of 560 m had an average ground slope varying between 5 and 12%. The study area was planted with Calabrian pine (*Pinus brutia* Ten.), stone pine (*Pinus pinea* L.), oriental plane (*Platanus orientalis* L.), and acacia (*Acacia* spp.) in the early 2000s (Fig. 2). The majority DBH of planted coniferous and deciduous trees in the study area was more than 10 cm. Average tree heights in the stand are between 6 and 7 m.

Equipment and software

In the study, a normal Haglöf Sweden's Mantax Blue caliper with 65 cm (Haglöf Sweden AB) and an iPhone 13 Pro Max (with 256 GB storage capacity) were used to measure tree stem diameters (Apple In, 2021). To activate the autonomous measuring specification of the smartphone, the "ForestScanner" newly introduced third-party app was employed.

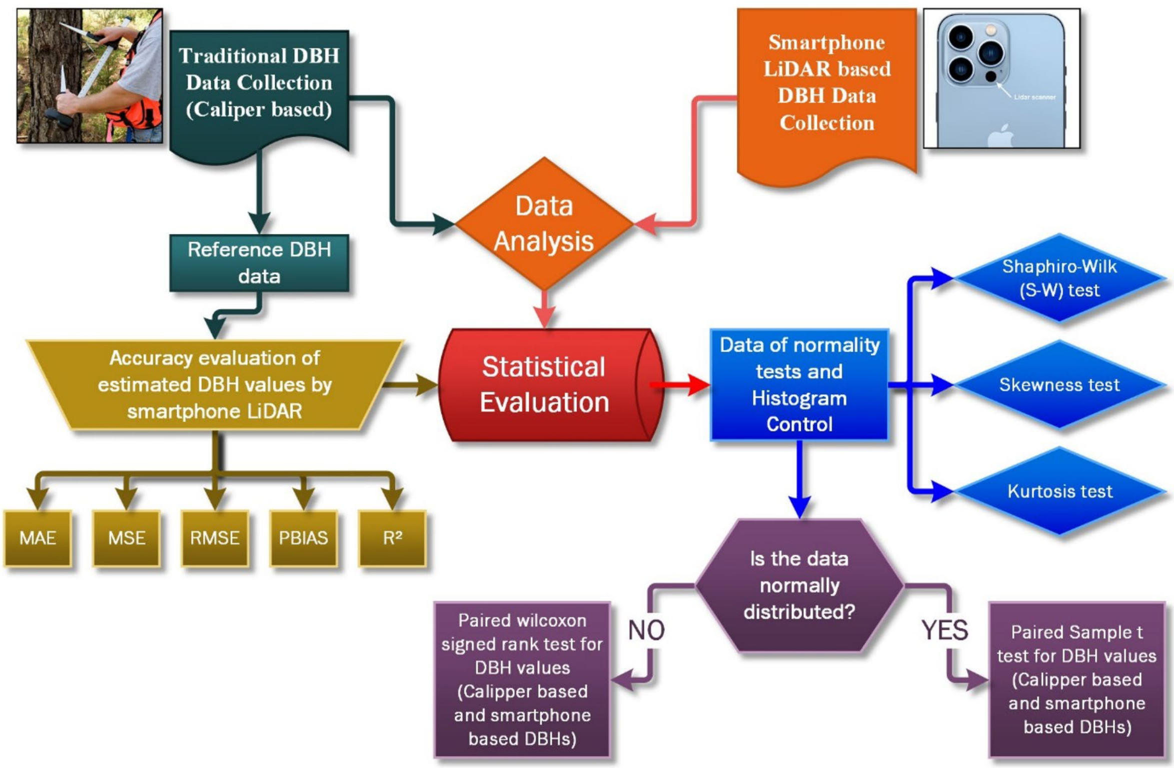

Fig. 1 The main workflow adopted in data collection and analysis stages

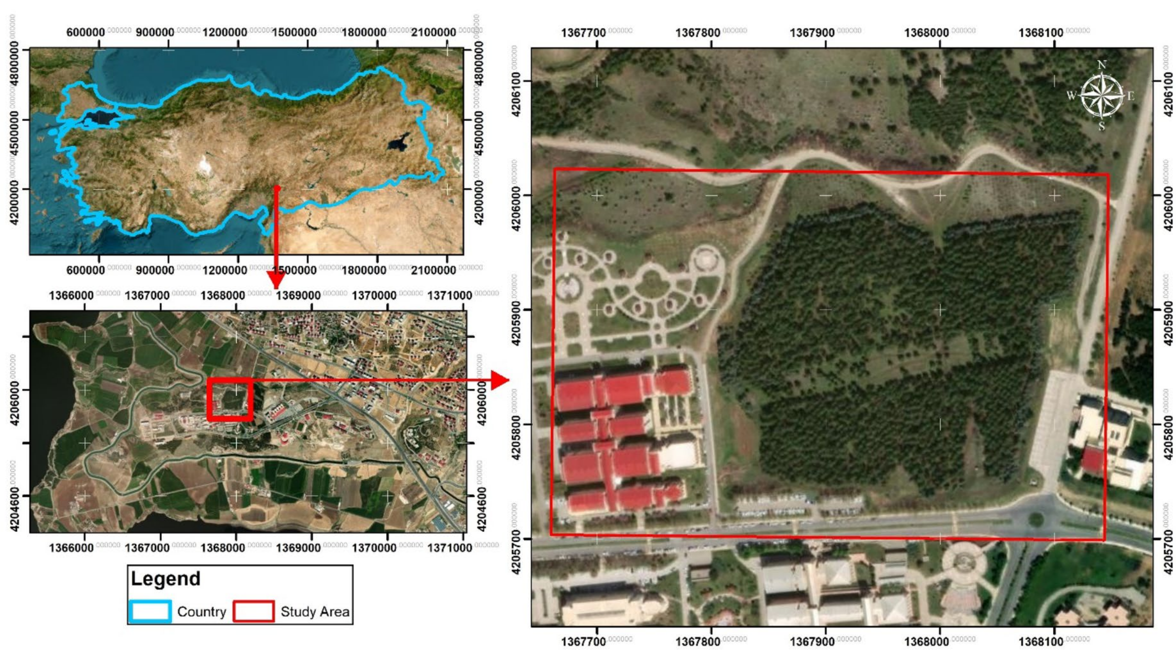

Fig. 2 General overview and geographic location of the study area

ForestScanner, which supports iOS structured devices, is for free on the App Store, and a general description can be found at https://forest-scanner.com (Fig. 3). ForestScanner (1.0.×) operates devices that have a time-of-flight LiDAR sensor. The software performs real-time tree stem segmentation using the YOLACT++fully convolutional network model. YOLACT++is a computer vision algorithm used for object detection and segmentation tasks. YOLACT++uses a set of techniques to improve its accuracy and precision, such as the use of multi-scale prediction and feature fusion, as well as the introduction of an iterative bounding box refinement process. These techniques help to reduce false positives and increase the accuracy of object segmentation. This is a pre-trained app and fits a circle to the cross-section of a tree by minimizing the sum of squares (Bolya et al., 2022; Tatsumi et al., 2022).

Fig. 3 Screenshots of the structured mesh models for trees and 3D point cloud view from a field study using the smartphone with the app. After the field measurements, a display screen of 3D point cloud and map of stems with DBHs on the app

Measurement process and procedure

In the study, 105 tree (55 Calabrian pine and 50 oriental plane) stems were measured outside the bark at breast height of operator (≅ 1.30m) by using a caliper and smartphone. Measurements were performed according to the ground on the uphill side of the tree (Fig. 4). First, the ForestScanner app run and required setups were done without calibration. Then, real-time measurement of the DBH at a distance of 3 m was applied using a smartphone as a measuring device. The app uses a geometrical algorithm-based equation that measures the deviation from the mean. The basic formula, which is used for circle fitting in LiDAR-based measurements, was structured on the sum of squares (SS) to fit a circle to the cross-section for tree DBH estimation (Eq. 1) (Tatsumi et al., 2022). As the walking path was parallel to the uphill side of the tree, the surveyor continuously scanned the tree from one side with a smartphone (Fig. 4a–c). The diameter average value obtained as a result of measuring the cross-section of the tree with a caliper was used as the DBH (Fig. 4d). In this context, it has been ensured that both the smartphone operator and the caliper operator follow the same trajectory in the field; thus, confusion in the measurement order was avoided.

$$SS(a,b,r) = \sum_i \left[\sqrt{(x_i - a)^2 - (y_i - b)^2} - r \right]^2 \qquad (1)$$

where a and b are the center coordinates of the circle, r is the radius, and x_i and y_i are the coordinates of data point i.

The app then estimated and recorded the stem diameter of the tree in a *.csv file. During the surveying activity with the smartphone, the screen was recorded as a video to identify the exact measurement points of the tree stem. This video was used to find and control the precise measurement points (Fig. 5a, b). In the case of irregular, forked, and curved trunk sections, two different diameters were measured above and below the tree's irregular stem using a caliper and a smartphone. Then, the arithmetic mean of the measurements was accepted as DBH (Fig. 5c, d). There were no markers on the tree stem. The smartphone was carried by hand without a monopod, tripod, or spirit level.

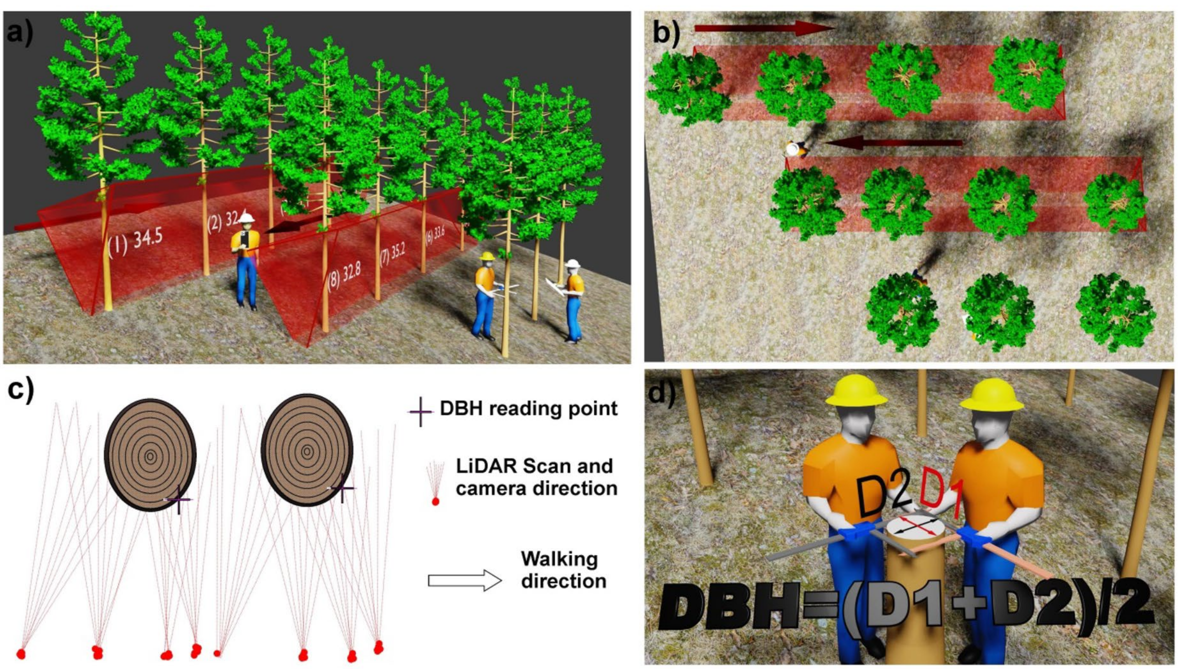

Fig. 4 Demonstration of smartphone use in measuring the stem diameter (**a**). A bird eye view (**b**) and plan view (**c**) of LiDAR-equipped smartphone surveying activity with single paths and directions in the field. Caliper use in measuring the stem diameter from two directions (**d**). Graphics are created in Blender software (https://www.blender.org/)

Fig. 5 Cross-checking and controlling the exact measurement point via screen records for the real-time estimated stem diameter (**a**) and the caliper-measured stem diameter (**b**). Measurement procedure of a tree with forked (**c**) and irregular stem (**d**)

Finally, a caliper was used to measure the diameter of the same 105 tree stems according to the tree stem measurement procedures (GDF, 2019). Additionally, diagonal measurements were made, and the average of the measurement values was used to reduce the errors during the measurement with the caliper (Fig. 4d). All measurements were noted in a notebook. The diameter measured by the caliper was then combined with the diameter value estimated by the LiDAR mounted on the smartphone and transferred to a computer for statistical analysis. The diameter measured by the caliper was used as reference data to reveal the accuracy and measurement error of the LiDAR-based real-time estimated diameters.

Statistical analysis and accuracy assessment

A paired-sample *t*-test and a Wilcoxon signed-rank test were used to analyze whether there was a significant difference between the estimated diameter (smartphone) and the directly measured diameter (caliper) in each technique. The normality of data and outliers according to the skewness, kurtosis, Shapiro–Wilk (S-W) tests, and the histogram graph was controlled (Table 2). The tests were performed for DBH data of Calabrian pine, oriental plane, and all tree species. In other words, statistical tests and error metrics were separately investigated for two species, and then, the data set was aggregated. All statistical analyses were performed using the NCSS 2022 data analysis software. To explore the measurement error between measured and estimated DBH, evaluation parameters, such as mean absolute error (MAE), mean squared error (MSE), RMSE, and percent bias (PBIAS), were calculated, respectively (Eqs. 2–5). In addition, as another evaluation parameter, the coefficient of determination (R^2) was also used for data comparison (Eq. 6). In the equations, N represents the number of measurements, y_i represents the measured value, $\hat{y}_i$ represents the predicted values, and $\overline{y_i}$ represents the mean of measurement values:

$$\mathrm{MAE} = \frac{1}{N} \sum_{i=1}^{N} \left| y_i - \hat{y}_i \right| \tag{2}$$

$$\mathrm{MSE} = \frac{1}{N} \sum_{i=1}^{N} \left(y_i - \hat{y}_i \right)^2 \tag{3}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left(y_i - \hat{y}_i \right)^2} \tag{4}$$

$$\mathrm{PBIAS} = 100 \times \frac{\sum_{i=1}^{N} \left(y_i - \hat{y}_i \right)}{\sum_{i=1}^{N} \hat{y}_i} \tag{5}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{N} (y_i - \hat{y}_i)^2}{\sum_{i=1}^{N} (y_i - \overline{y}_i)^2} \quad (6)$$

Results

In the study, it took approximately 18 min to measure the DBH of 105 trees with a smartphone. It took about 1 h and 15 min to measure the DBH of 105 trees with a caliper. According to the caliper measurements, the DBHs of the trees were a minimum of 8.50 cm and a maximum of 37.50 cm. Table 1 shows the details of obtained results for different tree species.

In the study, the RMSE values were calculated as 1.35 cm for the Calabrian pine and 3.06 cm for the oriental plane, respectively. The distributions of estimated and reference diameter values were partially similar to each other (Table 1). All performed MAE, MSE, RMSE, and PBIAS calculations of Calabrian pine showed higher accuracy than those of the oriental plane (Fig. 6). In this study, the R^2 was calculated as 91% for the Calabrian pine, 88% for the oriental plane, and 88% considering together all tree species (Fig. 7). All data showed a high linear correlation with a reasonable R^2. In Fig. 7 a and b, the diameter measurement of the smartphone and caliper seems to be quite close according to the measurement performance of the oriental plane.

According to the obtained results of the normality test, smartphone-based and caliper-based diameter measurement values show normal distribution (SW $p > 0.05$) for Calabrian pine and oriental plane

Table 1 Statistical summary of estimated and measured tree diameters

Tree species	Measurement technique	N*	Mean (cm)	Median (cm)	Minimum (cm)	Maximum (cm)	Std. deviation	Std. error	Variance
Calabrian pine	Smartphone	55	18.013	18.10	10.80	27.00	3.681	0.496	13.547
	Caliper	55	17.365	17.10	8.50	27.20	3.985	0.537	15.881
Oriental plane	Smartphone	50	24.392	23.15	10.65	40.10	6.468	0.915	41.840
	Caliper	50	22.846	21.45	8.80	37.50	5.719	0.809	37.711
All species	Smartphone	105	21.050	19.60	10.65	40.10	6.082	0.593	36.996
	Caliper	105	19.975	19.40	8.50	37.50	5.587	0.545	31.222

*N indicates the number of trees

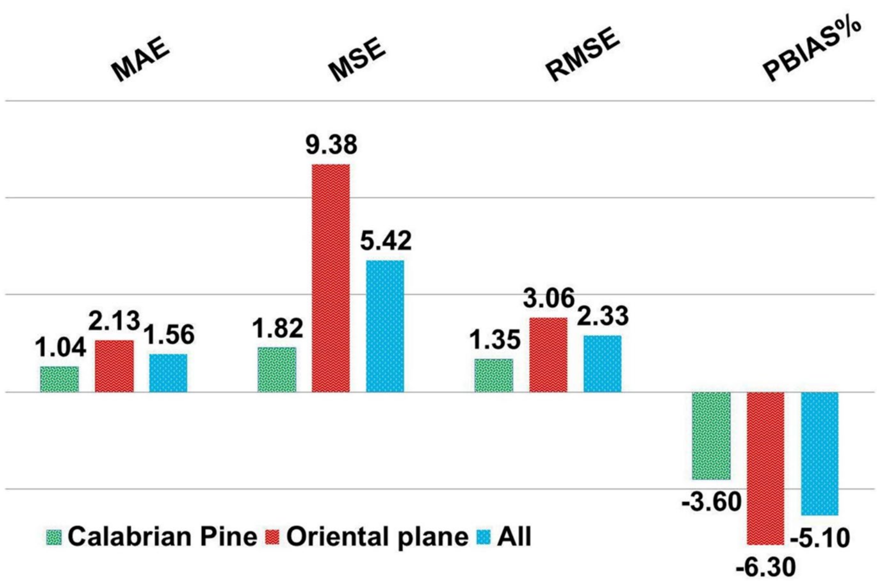

Fig. 6 Comparison of the error metrics for pine, plane, and all reference and estimated DBHs

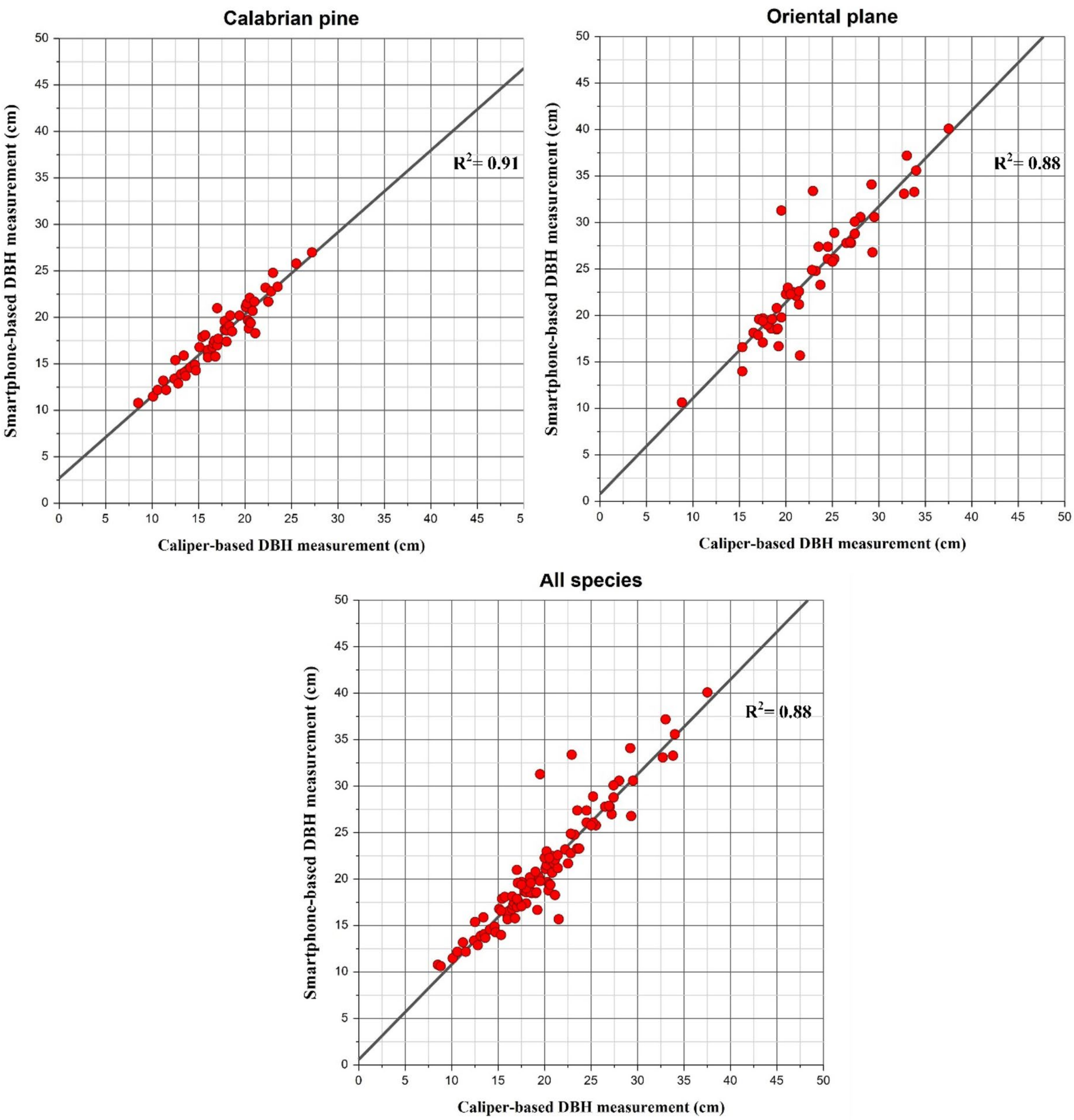

Fig. 7 Linear regression fitted plots for estimated and measured diameters for Calabrian pine (**a**) and oriental planer (**b**)

species. However, smartphone-based and caliper-based diameter measurement values show no normal distribution (SW $p < 0.05$) when all tree species are considered (Table 2). In addition, when the two tree species were evaluated separately, in terms of measurement technique, it was determined that the skewness coefficients were minimum 0.046 and maximum 0.424, and the kurtosis coefficient was minimum 2.614 and maximum 3.076. When two different tree species are evaluated together, it is seen that the skewness coefficient is minimum 0.625 and maximum 0.808 in terms of measurement technique, while the kurtosis coefficient is minimum 3.377 and maximum 3.553.

In addition, no outlier was detected for pine and plane groups. A high positive correlation emerged

Table 2 The results of the criteria used in the evaluation of the normal distribution

Tree species	Measurement technique	Skewness	Kurtosis	S-W
Calabrian pine	Smartphone	0.179	2.614	0.927
	Caliper	0.046	2.693	0.983
Oriental plane	Smartphone	0.315	2.528	0.569
	Caliper	0.424	3.076	0.190
All species	Smartphone	0.808	3.377	0.000
	Caliper	0.625	3.553	0.021

between each pair of trees measured and predicted. The results of the paired-samples *t*-test indicated that significant differences ($t(54)=4.013$; $p<0.01$) were detected for the Calabrian pine. The results of the paired-samples *t*-test indicated that significant differences ($t(49)=4.093$; $p<0.01$) were detected for the oriental plane. However, similar Wilcoxon signed-rank test results indicated a significant difference ($z=5.928$, $p<0.01$) when all tree species were considered.

Mean DBH diameters decreased by 0.65 cm and 1.55 cm for Calabrian pine trees and oriental plane trees, respectively (Table 3). According to the confidence interval of the difference, when the DBH measurements were repeated 1000 times, the calculated DBH changes were a maximum of 0.98 cm for the Calabrian pine and 2.31 cm for the oriental plane. Based on the statistical test results, it was expected that the reference and estimated DBHs would not differ from each other. However, looking at the error metrics and statistical results, lower precision and accuracy than normally expected were detected in the oriental plane DBH. A comparison of the reference and smartphone-estimated DBHs shows that there were overestimates. Overestimation was observed during visual and numerical control, especially in trees with forked stems (Fig. 8).

Discussion

Based on the success in DBH measurements, 105 tree stems were detected by two different (RS and traditional) measurement methods and compared. Calabrian pine and oriental plane diameters measured using a caliper were taken as reference DBH. The RMSE values for the Calabrian pine and oriental plane and all DBHs were calculated. R^2 coefficients and high positive correlations were calculated in the DBH comparisons of each species. Paired-sample *t*-test and Wilcoxon signed-rank test results showed significant differences between reference DBH and estimated DBH (Table 3), although the overall DBH RMSE value of 2.33 cm was within the range of estimates in the literature (Fig. 6; Table 4) (Vastaranta et al., 2015; Tatsumi et al., 2022). It is thought that the possible reason for this situation is that the accuracy in caliper-based diameter measurements taken for reference data may be affected by factors such as diameter differences in trees and differences in stem

Table 3 Summary table of paired-sample *t*-test and Wilcoxon signed-rank test analysis results for measurement pairs

Statistical test name	Pairwise comparison	Tree species	Mean ± SD	Std. error	95% confidence interval of the difference		*t*	*df*	*p*-value
					Lower	Upper			
Paired-sample *t*-test	Smartphone vs. caliper	Calabrian pine	0.647 ± 1.196	0.161	0.324	0.971	4.013	54	$p<0.01$
		Oriental plane	1.546 ± 2.671	0.378	0.787	2.305	4.093	49	$p<0.01$
Statistical test name	Pairwise comparison	Tree species	*z*	*p*-value					
Wilcoxon signed-rank test	Smartphone vs. caliper	All species	5.928	$p<0.01$					

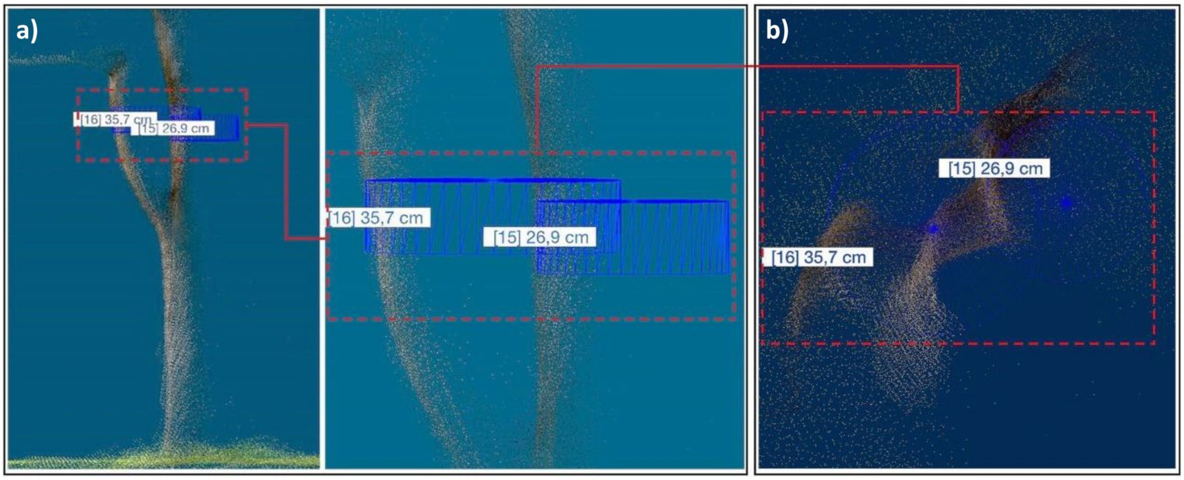

Fig. 8 Presentation of overestimated DBH of oriental plane with fork stem, and point cloud noise (side view of tree (**a**) and top view of tree (**b**))

structures (forked stems, inclinations, etc.). Similarly, Jurjević et al. (2020) compared conventional field measurements with low-cost, close-range RS-based measurements to determine tree height. Consistent with the findings obtained in our study, the accuracy of tree height may vary depending on the crown class and foliage in conventional field measurements.

In this study, considering the RMSE and coefficient of R^2 for Calabrian pine (*Pinus brutia* Ten.), our results showed much better performance than the study presented by Wang et al. (2022) for red pine (*Pinus resinosa*), white spruce (*Picea glauca*), and black spruce (*Picea mariana*) plantation sites, which reported an RMSE of DBH estimation varying from 2.82 to 8.24 cm (R^2 = 0.52). Compared to the DBH estimation results of Gollob et al. (2021), the lowest RMSE (3.13 cm) obtained using the ellipse model is still higher than the results of this study. In their study, they tested an iPad tablet–based LiDAR-derived point cloud processing in different forest types and structures. The error was lower than the accuracy in the diameter measurement comparison specified RMSE at 2.3 cm by Tatsumi et al. (2022). The error values determined by Tatsumi for multiple forest types, including conifer and broadleaf plantations of different stand ages and natural secondary forests, were similar to the total RMSE (2.33 cm) of the oriental plane and Calabrian pine diameters obtained in this study. Our findings from the oriental plane were also slightly similar to Mokroš et al. (2021), who investigated the accuracy of DBH estimates using an iPad Pro with a LiDAR sensor (RMSE = 3.14 cm) in European beech (*Fagus sylvatica* L.) and Norway spruce (*Picea abies* (L.) H. Karst.) forests. Chen et al. (2019) used a commercial portable terrestrial laser scanner device combined with the SLAM algorithm to demonstrate a new method for calculating the DBH, where the RMSE at 1.58 cm was more successful than our results for *Styphnolobium japonicum* (L.) SCHOTT. (syn. *Sophora japonica*), *birch*, and *Chinese pine* plantation sites. According to the comparison of earlier results with similar studies, close-range detection using consumer-grade LiDAR with computer vision technology is a promising technique for DBH estimation (Table 4). A smartphone with low-cost sensors is a reasonable device for DBH estimations; for example, the accuracy and precision of consumer-grade terrestrial LiDAR can reach 3.4 cm in *Quercus liaotungensis* and *Robinia pseudoacacia* L forests (Huang et al., 2011).

There could be many reasons for the slightly different RMSE and R^2 outcomes. First, the environment, tree species, and DBH distribution were or are different from similar studies. For example, when the operator moved quickly during the measurement, a shift in the image and mesh model was observed throughout the operating time. This means that factors such as the operator's walking speed, repeated measurements of DBH on the same tree, or incorrectly determined breast heights can increase measurement errors.

Table 4 The general brief and list of recently studied individual tree DBH estimations using a smartphone or similar device

Comparisons		Application/ software/ method	Tree groups	N**	DBH accuracy results		References
Measurement device	Reference data				R^2	RMSE	
Sony Xperia Z1 (compact mobile phone)	Caliper	TRESTIMA™	Coniferous and broadleaf	67	NA	Scots pine (1.4 cm), Norway spruce (2.3 cm) deciduous (1.8 cm)	(Vastaranta et al., 2015)
Lenovo Phab 2 Pro	Diameter tape	RGB-D SLAM	Coniferous and broadleaf	193	NA	The lowest: 0.39 cm, the highest: 2.22 cm, total: 1.26 cm	(Fan et al., 2018)
Android Xiaomi 3	Diameter tape	Computer vision and image processing	Not specified	15	0.99	0.217 cm	(Wu et al., 2019)
Smartphone camera	Caliper and measuring tape	Computer vision	Broadleaf	90	0.94	2.75 cm	(Putra et al., 2021)
DIY-based handheld device	Diameter tape	CNN-based software, deep learning	Broadleaf	121	NA	The lowest: 3.07 mm, the highest: 6.36 mm	(Song et al., 2021)
Apple iPhone 13 Pro and iPad Pro 2021	Not specified (traditional method)	ForestScanner	Coniferous and broadleaf	672	0.963 for iPhone, 0.961 for iPad	2.3 cm	(Tatsumi et al., 2022)
iPhone X	Caliper and laser caliper	iPhone measurement app	Coniferous and broadleaf	35	NA	NA	(Ucar et al., 2022)
iPad Pro	Diameter tape	Zappcha app and manually fitted circles	Coniferous	81	0.52	The lowest 2.82 cm, the highest: 8.24 cm total: 5.2 cm	(Wang et al., 2022)

**N represents the number of measured trees

DIY, do it yourself; *NA*, not available

Additionally in this study, it was observed that the accuracy and reliability of DBH estimates using a LiDAR-supported app for trees larger than 15 cm and straight stem form were more reliable (Gollob et al., 2021; Mokroš et al., 2021; Pueschel et al., 2013).

In this study, our primary assessment of accuracy and precision can be related to four main topics. These are (1) the low resolution of consumer-grade LiDAR on smartphones (Vogt et al., 2021), (2) the lack of measurement experiences with a smartphone, (3) the low sensitivity ofc the app-adaptive architecture, and (4) the size of the sampling area and tree feature. Besides, this study was conducted only during the vegetation period for 55 coniferous and 50 deciduous trees. Different accuracy results can be observed when this application is performed under different conditions and for different sample sizes. Due to the availability of pre-trained models, the success of the tree stem mesh model construction is very rapid. The trees (pine and plane stem with bark) can be completely detected with high visual quality (Fig. 3).

The measurement of DBH obtained from LiDAR and vision technology, such as high accuracy and precision tools, is still controversial today (Clark et al., 2000; Dassot et al., 2011; Xie et al., 2020).

Compared to other expensive but laborious (i.e., terrestrial laser scanners and hardware) mobile LiDAR systems with high spatial accuracy (Liang et al., 2018; Mokroš et al., 2021), low-cost consumer-grade LiDAR now offers the opportunity to work at very reasonable cost and accuracy. In short, research into newly developed consumer-grade smart technologies with passive and active sensors (such as cameras and LiDAR) is rapidly increasing due to the proven accuracy and simplicity in forestry-related studies. Research into cost-effective sensors and the development of user-friendly software for single tree measurements in forestry will be beneficial in scientific research in the coming years. In addition, the widespread use of technology will enable the determination of standards in the use of national forest inventory studies. Although the SLAM algorithm has proven itself, it has not yet found a place in national forest inventory studies. At this point, it is believed that the regulations should be updated by creating a legal infrastructure.

Also, a smartphone-based LiDAR system does not necessarily need notebooks and an extra person. One person can operate and measure the diameter of tree stems. However, there must be enough memory, as the software crashes when the data reaches about 238 MB of memory. The application then stops recording real-time 3D point cloud generation and measuring diameters. Due to an app crash, users do not have to restart. When the application was rerun, the measurement continued without loss of data in another job file.

Additionally, the algorithms used in tree diameter measurements are also used with training data for species-specific trees with varying stand characteristics. For this reason, in these and similar applications, the apps can provide users with the opportunity to increase measurement accuracy by collecting training data specific to their own research. Research is needed to use low-cost LiDAR-assisted AR technology devices to measure DBH at different distances, angles, and rotations in coniferous and deciduous tree species.

In addition, the technology has great potential, despite some limitations. First, LiDAR or SLAM-based technologies are not widely used in daily-use mobile or smart devices. Also, LiDAR sensors have some limitations like limited data acquisition range (~5 m). Range limitations result in the inability to measure all tree attributes, such as tree height, stem volume, or crown closure. All other attributes will be available when these limitations are removed with the development of technology.

Conclusion

In this study, a LiDAR-equipped smartphone with third-party software was used to measure the diameter of the tree stem. The interface of ForestScanner is user-friendly and simple to use. The smartphone-based DBH estimation method for deciduous and coniferous trees was reasonably accurate (overall RMSE = 2.33 cm).

This study has the advantage of revealing the positions of trees (XY) and digital elevation model (DEM) according to existing traditional measurements. Structure from real-time semantic mesh architecture (SfRSM), which uses deep learning techniques in the determination and segmentation of object features by using motion and LiDAR in an AR environment, is a novel technique that results in precise, indirect measurements. However, considering the current pre-trained model, further training data is still necessary to accurately measure the fork stems. The accuracy of classification or segmentation algorithms is crucial to obtain more accurate results, and it is important to focus on training or improving these algorithms. Emphasizing this aspect can lead to more reliable and precise results, which is especially crucial in fields where accurate measurements are important, such as in forestry, ecology, and environmental sciences.

According to the comparison between smartphone- and caliper-based measurements, individual tree diameter values are significantly different ($p < 0.05$). Fork stem and irregular stem estimations are effective factors in accuracy. Trees with a fork stem have very low accuracy. This technique is a quick and convenient method compared with traditional measurement. If this application is adjusted/added according to the basic tree diameter measurement and forest mensuration principles of forest inventory, it will become a more advanced method for automatic DBH measurement. For example, automatic estimation of species-specific tree volume and height should be added as an option. In this context, artificial intelligence (AI) presents a significant opportunity for the forestry sector. With the advancements in technology and decreasing hardware costs, AI algorithms can be developed and utilized for forestry inventory studies, leading to the digitalization of the sector. One of the most significant benefits of AI-based devices is the ability to automatically identify tree species, as well as measure volume and height, among other inventory parameters. This automation will undoubtedly eliminate one of the most significant expense sources in forestry, which is the cost of manual inventory data collection. Therefore, incorporating AI into forestry management practices has enormous potential to increase efficiency, reduce costs, and improve the accuracy of inventory data.

Further experiments are needed to investigate the uncertainties associated with trees of different stem forms, species (coniferous or deciduous), different work environments, and different types of LiDAR and LiDAR-based app scanners. Since the current version of the utilized app does not have the option to transfer the recorded 3D point cloud to a computer, users cannot use a different algorithm than the one provided by the app. To analyze the performance of a low-cost LiDAR-based DBH estimation for further discussion, different apps should be examined.

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Data availability Data will be made available on request.

Declarations

All authors have read, have understood, and have complied as applicable with the statement on "Ethical Responsibilities of Authors" as found in the Instructions for Authors and are aware that with minor exceptions, no changes can be made to authorship once the paper is submitted.

Conflict of interest The authors declare no competing interests.

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