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Research article

Medición de parámetros de inventario forestal en bosques plantados, mediante tecnología *LiDAR*: Comparación de métodos

Measuring forest inventory parameters in planted forests using LiDAR technology: Comparison of methods

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Abstract
Forest inventory describes the quantity, size, and quality of the trees in a forest and the characteristics of the space where they grow. Traditionally, a forest inventory is carried out manually, with calipers to measure the diameter at breast height (*DBH*), and devices that use geometric principles, such as the clinometer for the estimation of total height (*TH*). This paper documents the applicability of a tablet with integrated LiDAR technology for the measurement of forest inventory parameters, by comparing dendrometric data obtained with LiDAR and traditional methods: geographic position, *DBH*, *TH*, crown diameter (*CD*) and clear stem height (*CS*) of individual trees in a planted coniferous forest. A simple linear regression analysis was performed with each variable, and a *t*-student test was applied to determine differences between means, as well as to calculate the Root Mean Square Error (RMSE) to measure the error between predicted and observed values. The results show a R^2=0.99 and *RMSE*=0.657 cm for *DBH*; a R^2=0.98 and a *RMSE*=0.369 m for *TH*; a R^2=0.95 and *RMSE*=0.341 cm for *CD*, and a R^2=0.97 and *RMSE*=0.208 cm for *CS*. The total scanning time for LiDAR data acquisition was 3.4 times less than traditional forest inventory time. The proposed method for forest inventory in planted forests using the mobile device is reliable, accurate, and less time-consuming than the traditional approach.
Key words: Terrestrial laser scanning, iPad Pro®, forest parameters, augmented reality, free to use software, mobile LiDAR sensor.

Resumen

El inventario forestal describe cantidad, tamaño y calidad de los árboles de un bosque, así como las características del espacio donde crecen. Tradicionalmente, el inventario forestal se realiza manualmente, con calibradores (forcípulas) para medir el diámetro a la altura del pecho (*DAP*), y dispositivos que utilizan principios geométricos, como el clinómetro para la estimación de la altura total (*AT*). En el presente trabajo se documenta la aplicabilidad de una tableta con tecnología *LiDAR* integrada para la medición de parámetros de inventario forestal, mediante la comparación de datos dendrométricos obtenidos mediante *LiDAR* y con métodos tradicionales: posición geográfica, *DAP*, *AT*, diámetro de copa (*DC*) y altura de fuste limpio (*FL*) de árboles individuales, en un bosque plantado de coníferas. Se realizó un análisis de regresión lineal simple con cada variable y se aplicó una prueba *t-student*, para la determinación de diferencias entre medias, así como el cálculo de la Raíz del Error Cuadrático Medio (*RECM*) para medir el error entre los valores predichos y los observados. Los resultados muestran una R^2=0.99 y *RECM*=0.657 cm para el *DAP*; R^2=0.98 y un *RECM*=0.369 m para la *AT*; R^2=0.95 y *RECM*=0.341 cm para el *DC* y R^2=0.97 y *RECM*=0.208 cm para el *FL*. El tiempo total del escaneo para la adquisición de datos *LiDAR* fue 3.4 veces menor al tiempo del inventario forestal tradicional. El método propuesto para inventario forestal en bosques plantados mediante el dispositivo móvil es confiable, preciso y consume menos tiempo, en comparación con el enfoque tradicional.

Palabras clave: Escaneo láser terrestre, *iPad Pro*®, parámetros forestales, realidad aumentada, *software* de uso libre, sensor *LiDAR* móvil.

Introduction

The increase in the demand for products and services obtained from the forest, together with the need to preserve the environment and natural resources, has led to the establishment of planted forests to meet these demands more efficiently. In addition, they often contribute to reducing pressures on natural forests, which are increasingly focused on biodiversity conservation and the regulation of natural resources such as soil and water (Musálem, 2006). Therefore, the development of accurate methods for timber inventory, oriented to estimate the structural parameters of planted forests, is a crucial forestry tool for predicting forest productivity; besides, it can provide a quantitative assessment of forest stands.

The forest inventory describes the quantity, size, and quality of the trees in a forest, as well as other characteristics of the area where they grow (Ayrey & Hayes, 2018). It is also the basis for analysis and planning, the starting point for sustainable forest management. Estimation of single-tree and whole-stand information is one of the central tasks of forest inventory.

In Mexico, traditionally, forest inventory data are collected using manual measuring equipment such as diameter tapes or calipers for normal diameter (*DBH*), clinometers for total (*TH*) or clear stem (*CS*) height, and flexometers for measuring crown diameters (*CD*). In practice, this is time-consuming, labor-intensive, and costly (Liang et al., 2018; Ritter et al., 2017). This strategy, carried out directly in the forest, is the basis for studies using indirect measurement methods. This requires evaluating and comparing alternative methods such as remote sensing to derive tree parameters (Ciesielski & Sterenczak, 2019; Hernández, 2020).

Terrestrial laser scanning (TLS) is increasingly recognized as an alternative to conventional forest inventory methods (Liang et al., 2016; Newnham et al., 2015). In recent years, automatic algorithms for tree detection and measurement using TLS have been successfully developed (Calders, 2015; Elsherif et al., 2018; Estornell et al., 2017). TLS, by measuring distances to multiple points on the surfaces of surrounding objects, builds 3D point clouds from which the sizes and spatial distributions of trees can be quickly estimated. However, the high cost of TLS equipment (typically priced over US $40 000) has put it out of reach of many potential users (Mokroš et al., 2021; Tatsumi et al., 2021; Wang et al., 2022). In addition, their weight has also been a challenge, making it difficult to transport them to and within some areas, which adds costs due to time spent in moving and handling them (Gollob et al., 2021).

The need for specialized software is another factor that has limited the collective use of TLS (Elsherif et al., 2018; Hernández, 2020). Alternative methods utilized to overcome this are mobile laser scanning (MLS) (Liang et al., 2014) and short-range photogrammetry (Tomaštík et al., 2017). Certain studies indicate that these mobile devices can acquire 3D point clouds in forests (Gollob et al., 2021; Mokroš et al., 2021; Wang et al., 2022). However, to derive tree-level information from these clouds (*e. g.*, stem diameter), further analysis must be performed on a separate device with multiple software packages (Wang et al., 2022).

Currently, there is an alternative use of easy-to-use and low-cost applications for iPhone®/iPad®, personal mobile devices (smartphones or tablets) for registering 3D information of individual trees in a forest inventory context. Since 2020, Apple Inc.® (Apple Inc., 2022) has incorporated a light detection and ranging (LiDAR) sensor in some iPhone® and iPad® models (Pro versions), which are available with a price tag of approximately USD $1 000 and are lightweight (187-684 g) compared to other LiDAR devices in the market and also include a programming interface for augmented reality (AR) applications, making it possible to access LiDAR-generated 3D point clouds with personal mobile devices. This device works with the integrated LiDAR sensor, camera system, motion sensors (three-axis gyroscope, accelerometer, Inertial Measurement Unit, barometer, ambient light sensor), and a GPS/GNSS system (Apple Inc., 2022).

Tatsumi et al. (2021) developed and tested a free mobile application, called ForestScanner® (MAPRY Co. Ltd., 2022), that enables laser scan-based forest inventories using the LiDAR sensor embedded in an iPhone®/iPad Pro® requiring no manual or post-processing analysis of 3D point clouds, while the user scans trees with the device, the application estimates the *DBHs* and their spatial coordinates, based on real-time object detection and circle adjustment (Tatsumi et al., 2021), using an augmented reality (AR) platform and LiDAR sensor (Kuželka et al., 2020).

The objectives of this work were: (1) To test the performance of the iPad Pro®, using LiDAR and AR applications to estimate geographic position, *DBH*, *TH*, *CD*, and *CS* on individual trees; and (2) To compare the results thus obtained with measurements performed using traditional methods. The evaluation and determination of the potential of the iPad Pro® in forest inventories based on the level of precision in the estimation of the proposed parameters will make it possible to establish and provide an innovative, lower-cost, and precise method applicable to forest inventories in planted forests.

Materials and Methods

Data were collected from 20 sampling sites established in a mixed planted forest aged approximately 35 years, with an area of 4.64 ha, located on the banks of the *Cointzio* dam, 12 km Southwest of the city of *Morelia*, state of *Michoacán*, Mexico (19.621 N; -101.262 W). The main species in the plantation are: *Cupressus lindleyi* Klotzsch *ex* Endl. and *Pinus leiophylla* Schiede *ex* Schltdl. & Cham., as well as isolated specimens of *Eucalyptus* sp. and *Casuarina equisetifolia* L.; these taxa were part of forests planted for soil restoration and conservation (Figure 1).

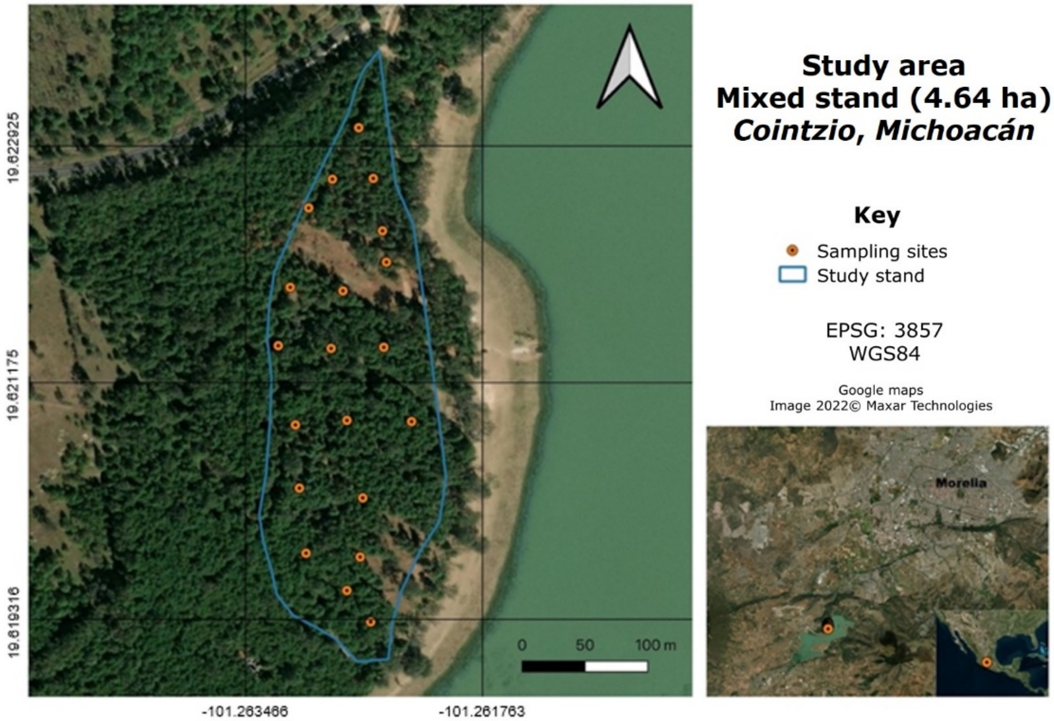


Figure 1. Study stand and location of 20 sampling sites.

Systematic sampling was applied (West, 2009) in 60×60 m sampling lines; the sites were circular, measuring 400 m^2 (radius=11.28 m), and were located within a sampled area that amounts to 17.2 % of the total planted forest (Cochran, 1977). Plots were defined as the sampling and scanning unit, considering the plot sizes often adopted in national and international forest inventory programs (*Comisión Nacional Forestal* [Conafor], 2014), given that this sample size was also used by Tatsumi et al. (2021), who developed the app used in the present study, as well as in iPhone®/iPad® evaluations (Gollob et al., 2021; Mokroš et al., 2021). The sites were located using a model eTrex 20 Garmin® GPS (Figure 1), and the geographic positions of the central tree were recorded. All trees with a *DBH*≥7.5 cm were measured with a model MANTAX BLUE Haglöf Sweden® (60 cm) caliper. The *TH*, *CS*, and *CD* variables were also recorded with a model PM-5/360 Suunto® clinometer was used for the first two parameters. The *CD* was measured with a model TP50ME

Truper® measuring tape in the North-South and East-West directions; the projection of the ends of the tape on the ground was taken as a reference, and the two measurements were averaged.

Inventory data collection

The *DBH* of trees at each site was measured using the free ForestScanner® app (MAPRY Co. Ltd., 2022; Tatsumi et al., 2021), installed on iPad Pro®, so that each sampling site was scanned; this application generates point clouds and a database of the estimated the *DBH* automatically. The ForestScanner® device scans objects within a distance of 5 m (maximum scanning range of the sensor), acquiring a 3D point cloud of the surrounding object surfaces. ForestScanner® shows the point cloud and 3D triangle meshes on the screen in real time, allowing visual recognition of the scanned surfaces. As the trees are scanned, the diameters of the stems appear instantly on the screen in AR form, and the point cloud is colored with RGB information collected by the device's cameras (complete procedure in S1 video: https://drive.google.com/file/d/1al5wPJMeshOneTqk_V8XIBrO6fgAKZM2/view?usp=sharing).

Data acquisition with the iPad Pro® laser sensor was initiated at the center of each sampling site. The scanning was performed by walking at normal speed, while the LiDAR sensor collected the 3D measurement data. During the scanning, ForestScanner® tracks the relative coordinates of the device from the starting point based on the inertial measurement unit (IMU) (GNSS navigation). The absolute location (geographic coordinates) of the starting point is determined by the GNSS integrated in the iPad Pro®.

It is worth mentioning that the newest models of the iPhone 15 Pro® and Pro Max® (September 2023) already have a precision dual-frequency GPS (Apple Inc., 2022). Tatsumi et al. (2021) and MAPRY Co. Ltd. (2022) provide the steps for surveying a sampling site and detailed specifications for its use (https://mapry.co.jp/). The generated 3D models and data files were exported to a laptop computer.

Total height, crown diameter, and clear stem height

The Arboreal® application was utilized to estimate the *TH*, *CD*, and *CS* in individual trees at each sampling site (Arboreal AB, 2022). The *TH* and *CS* were measured in a very similar way as with Suunto® clinometer, with the big difference that, when using the iPad Pro® sensor technology, the distance between the sensor and the tree to be measured is not relevant: it only has to be >10 m from the base of the tree, but when the trees are too high (>30 m) it is convenient to move away 15 to 20 m (the complete procedure is shown in video S2): https://drive.google.com/file/d/1Ncvs5HSAFy2iRrLtJo0NYZUOrd3WRY1R/view?usp= sharing). Another advantage is that the measurements of each tree are recorded in individual files on the iPad Pro®, and both the database of measured trees (.csv) and the images of the measurements (.jpg) can even be shared with other users (via AirDrop®, email or WhatsApp®). The *CD* of each tree is measured simultaneously with its *TH* and *CS* (video S2).

Data evaluation and analysis

The variables were analyzed by comparing the value of the dendrometric variables estimated in the traditional way (reference measurement) *versus* the value obtained through the alternative technology (LiDAR+AR). The hypothesis was to demonstrate the equality of the values of the variables with both methods. Each variable was estimated with a simple linear regression analysis (Equation 1), using the Coefficient of determination (R^2) and the Root Mean Squared Error (*RMSE*) (Infante & Zárate, 2012):

$$Y = a + b X + \varepsilon \quad (1)$$

Where:

Y = Dependent variable whose value was obtained through the conventional method

a = Coefficient to be estimated, corresponding to the intercept (constant term) that represents the value of Y when X is 0

b = Coefficient to be estimated that corresponds to the slope and indicates how much Y changes for each unit of change in X

X = Independent variable obtained by LiDAR+AR

$\mathcal{E}$ = Random error of the model, which indicates the variations of Y that are not explained by X

A *t*-student test was applied to test the hypothesis that the two measurement alternatives are significantly different in order to determine the differences between sample variances and construct the confidence interval. The *RMSE* statistic

(Equation 2), which measures the amount of error between two sets of data, was also utilized. In this case, it compares a predicted value (V_{LAR}) and an observed or reference value (V_{Tra}) (Infante & Zárate, 2012).

$$RMSE = \sqrt{\frac{\sum_{i}^{n}(V_{LAR} - V_{Tra})^2}{n}} \qquad (2)$$

Where:

V_{LAR} = Value of the variable (*DBH*, *TH*, *CD*, and *CS*) estimated or predicted by the regression

V_{Tra} = Reference value of the same parameters, estimated with traditional methods

n = Number of samples used in the analysis (446 trees) from 20 sampling sites

Results

The scanning time per site to record *DBH* and geographic position using the ForestScanner® LiDAR app ranged from 0.8 to 3.8 min, with an average of 2.3 min per site. A total of 45.6 min was required for the 446 total trees at the 20 sampling sites, without considering the travel time between sites. This registration activity was carried out by a single person (Table 1).

Table 1. Comparación del tiempo y número de personas requeridas para medir los parámetros de inventario (446 árboles) con el método propuesto (iPad Pro®) *versus* el método tradicional.

	LiDAR method+AR					**Traditional method**				
	iPad Pro® and Arboreal®				**Total time**	**Caliper**	**Clinometer**		**Measuring tape**	**Total time**
Measured parameters	***DBH* and 446 coordinates**	***TH***	***CS***	***CD***	**All the variables**	***DBH* and 1 coordinate**	***TH***	***CS***	***CD***	**All the variables**
Number of people	1*		1*		1	2**		2**		2**
Time spent (h)	0.76		3.55		4.31	3.99		10.65		14.64
People per hour	0.76		3.55		4.31	1.96		5.33		7.32

* Single operator, measurements are automatically recorded on the device. ** Someone to measure the *DBH*, *TH*, *CS*, and *CD* and one more person to record the data in a format, which must then be entered into a computer program. *DBH* = Normal diameter; *TH* = Total height; *CD* = Crown diameters; *CS* = Clear stem.

The measurement time for the reference *DBH* data, carried out by two people with a caliper and only the central tree coordinate, averaged 12 min per site, adding up to 239.5 min (3 h 59.4 min). In contrast, the iPad Pro® method reduced the time required to measure the *DBH* to 19.03 %, *i. e.*, 5.25 times less (239.5 min *vs.* 45.6 min), with the bonus that it is performed by a single person (Table 1). Furthermore, all data for each of the scanned trees —including their geographic position— are recorded in an exportable digital file, unlike the traditional inventory, which records only the coordinates of the central tree and requires all data and inventory information to be subsequently captured through additional cabinet work.

The measurement time for the *TH*, *CD*, and *CS* parameters with the Arboreal® app ranged between 2.5 and 18.9 min, with an average of 10.7 min per site and a total time of 213.2 min (3 h 33 min), and was performed by a single person (Table 1). In contrast, with classical measuring instruments for *TH*, *CS*, and *CD* with two persons, the total measurement time was 638.8 min (10 h 39 min). The use of the iPad Pro®

reportedly reduced the number of hours and people required to perform these measurements to 33.37 % (tables 1 and 2), that is, they took 3 times less (638.8 min *vs.* 213.2 min). An additional advantage is that only one person carried them out, and all the data were recorded in an exportable digital file, unlike the traditional method, which requires two people and the capturing of the field information at the office, which implies a greater time and office staff consumption.

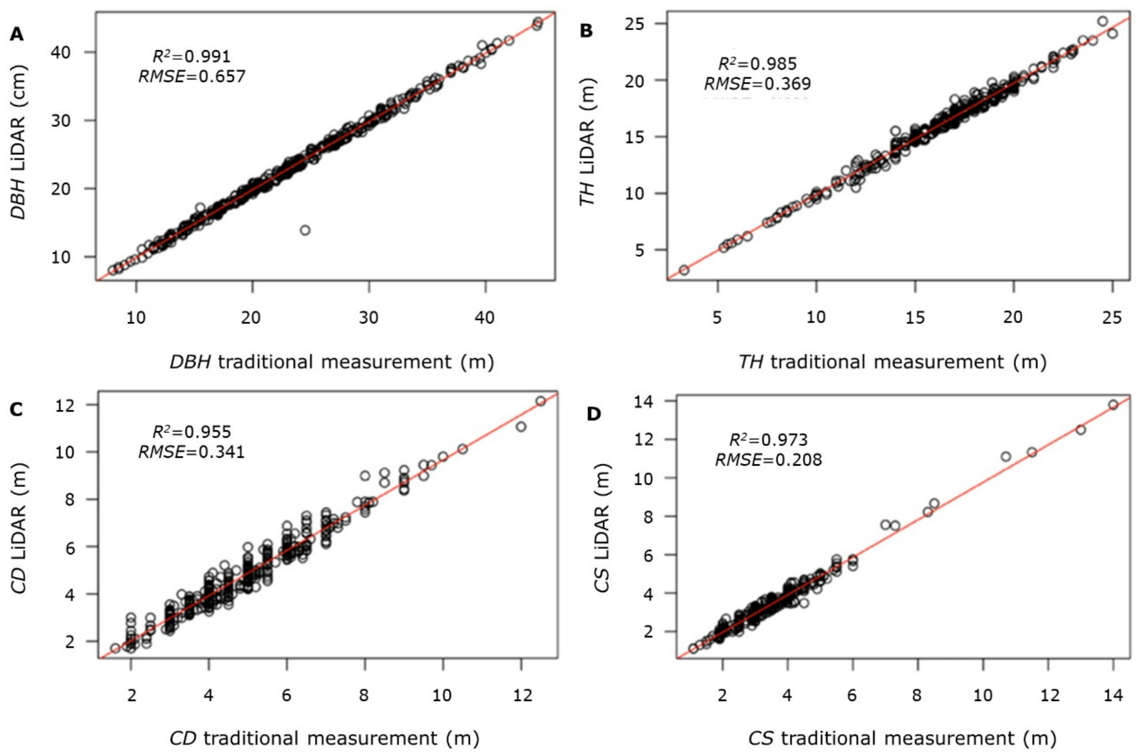
Table 2. Statistics derived from the two-sample *t*-student test, between the time consumed in LiDAR+AR measurements and with the traditional method.

Parameter	*t*-value	Degrees of freedom	*p*-value	Sample estimates	
				Mean *x*	Mean *y*
DBH	9.775	20.669	3.36E-09	11.97	2.28
TH-CD-CS	7.558	25.275	6.06E-08	31.94	10.66

DBH = Normal diameter; *TH* = Total height; *CD* = Crown diameters; *CS* = Clear stem.

A *t*-test showed significant differences (p-value<0.05) in the measuring times between the two methods (Table 2).

A linear regression comparison of the parameters analyzed showed an overall good fit in terms of the deviation of the estimates with the LiDAR+AR technology and the reference measurements, with an R^2=0.991 and *RMSE*=0.657 cm for *DBH*, an R^2=0.985 and *RMSE*=0.369 m for *TH*, an R^2=0.955 and *RMSE*=0.341 cm for *CD*, and an R^2=0.973 and *RMSE*=0.208 cm for *CS* (Figure 2, Table 3).



A = *DBH*; B = *TH*; C = *CD*; D = *CS*.

Figure 2. Linear regression of the relationship between LiDAR+AR measurements and the tree parameter measurements using the traditional method.

Table 3. Values of the coefficients (*a* and *b*) estimated for the tree parameters through linear regression.

Parameter		Statistic				Residual standard error (444 degrees of freedom)	R^2	Statistic *F* (444 degrees of freedom)	*p*-value
		Estimated coefficient	Standard error	*t*-value	*Pr*(>|*t*|)				
DBH	a	-0.122	0.107	-1.146	0.252	0.658	0.991	50 490.0	2.2E-16
	b	0.999	0.004	224.691	2.0E-16				
TH	a	0.030	0.094	0.320	0.749	0.370	0.985	29 870.0	2.2E-16
	b	0.985	0.006	172.840	2.0E-16				
CD	a	0.104	0.050	2.087	0.038	0.341	0.955	9 462.0	2.2E-16
	b	0.956	0.010	97.272	2.0E-16				
CS	a	0.008	0.028	0.272	0.786	0.208	0.973	16 260.0	2.2E-16

b	0.976	0.008	127.519	2.0E-16

DBH = Normal diameter; *TH* = Total height; *CD* = Crown diameters; *CS* = Clear stem.

Welch's two-sample *t*-test also confirmed a good fit for the prediction equations of the dendrometric parameters measured with the LiDAR+AR and traditional methods (Figure 2, Table 3) for measuring the *DBH*, *TH*, *CD*, and *CS* and exhibited no significant differences (*p*-value>0.05) (Table 4). Therefore, it may be assumed that there is equality between the estimates of such parameters measured with the iPad Pro® as an alternative method (LiDAR+AR) and those obtained in a conventional way (caliper, clinometer, and measuring tape), due to the high R^2 values and low *RMSE* values.

Table 4. Statistics of the two-sample *t*-student test using LiDAR+AR measurements and the traditional method.

Parameter	Two-sample t-test				
	***t*-value**	**Degrees of freedom**	***p*-value**	**Sample estimates**	
				Mean *x*	**Mean *y***
DBH	0.323	889.990	0.746	22.966	22.814
TH	0.999	889.950	0.317	16.231	16.025
CD	0.978	889.570	0.328	4.787	4.680
CS	0.884	889.890	0.377	3.414	3.338

DBH = Normal diameter; *TH* = Total height; *CD* = Crown diameters; *CS* = Clear stem.

Discussion

LiDAR scans with iPad Pro® successfully detected 100 % of the trees with *DBH*>7.5 cm. This implies that the scans and point clouds are generated completely in the area of the stem to be measured (height of 1.30 m from ground level) and agrees with the results obtained by Bobrowski et al. (2022), Brach et al. (2023) and Çakir et al. (2021), who also detected 100 % of the measured trees. Other studies cite lower detection percentages, comparing the use of LiDAR scanning apps for iPad Pro®: Gollob et al. (2021) and Wang et al. (2022) document 85 to 97 % detection with mobile laser scanning (MLS) and personal laser scanning (PLS); Bauwens et al. (2016), Ko et al. (2021) and Zhou et al. (2019) also detected percentages below 100 % in trees with *DBH*>10 cm. The detection rate decreases in sampling plots with high tree density and *DBH*<5 cm (Bauwens et al., 2016; Gollob et al., 2021; Zhou et al., 2019).

Çakir et al. (2021) utilized the iPad Pro® LiDAR sensor to generate 3D models and estimate the *DBH* variable comparing it with estimates made using TLS. The best fit was for *DBH* estimation with TLS (R^2=0.995, *RMSE*=7.02 cm); with iPad Pro®, the R^2 was 0.995, and the *RMSE*, 8.72 cm. On the other hand, Bobrowski et al. (2022) compared circumference at breast height (*CBH*) measurements with TLS and point clouds generated by the LiDAR sensor of the iPad Pro® using the Abound Capture® app: they estimated an R^2= 0.899 and an *RMSE*= 7.41 with the tablet, and an R^2=0.912 and *RMSE*=6.51 utilizing TLS.

When Brach et al. (2023) compared *DBH* measurements with traditional methods *versus* point clouds generated with iPad Pro® and recorded a fit with an R^2=0.990 and an *RMSE*=5.340 cm. It should be noted that the LiDAR scanning applications used by Bobrowski et al. (2022), Brach et al. (2023), Çakir et al. (2021), Gollob et al. (2021) and Wang et al. (2022) to measure *DBH* were not developed for this purpose, unlike the app used in the present study (ForestScanner®), which was developed exclusively for the purpose of measuring *DBH* in forest inventories (Tatsumi et al., 2021). This situation allowed to improve the detection of all the trees proposed herein for inventory (*DBH*>7.5 cm), as well as the quality of the point clouds (rendered denser).

Compared to traditional measurement techniques, the total measurement time with the iPad Pro® was 3.4 times faster (tables 1 and 2), in agreement with the findings of Gollob et al. (2021), Ko et al. (2021), and Wang et al. (2022), whose measurement times for *DBH* were 3.2, 2.5, and 3.8 times faster, respectively.

As for the *TH* variable, the literature only indicates its estimation with devices such as mobile LiDAR (Heo et al., 2019) and smartphones with RGB-D SLAM (Ahamed et al., 2023; Fan et al., 2018). No studies using this type of technology in mobile devices for estimating the *CD* and *CS* were identified.

Gollob et al. (2021) noted that, in general, *DBHs*>5 cm were overestimated, and *DBHs*>35 cm were underestimated, and so did Wang et al. (2022), regardless of whether the iPad Pro® or PLS were utilized. Moreover, Bobrowski et al. (2022), Brach et al. (2023), Çakir et al. (2021) and Wang et al. (2022) found that the errors were due to the lack of post-processing of the point clouds generated with the application, which, according to Hernández (2020), must be exported to a computer using specialized software.

According to the results of the present study for the four parameters analyzed, the regression line fit accounts for 97-99 % of the variability in the data (Figure 2; Table 4). This suggests a strong correlation between the methods evaluated; the minimal differences in measurements between them are due to the linear relationship established, so that the measurements made with one method can be predicted with high accuracy based on those carried out with the other. This is because the algorithms of the ForestScanner® app were created exclusively for the detection and measurement of *DBH* in conifers, and their use has been tested in different conditions of natural and planted forests (MAPRY Co. Ltd., 2022; Tatsumi et al., 2021).

The graphic comparisons (Figure 2) show that the relationship between the estimates of the parameters carried out with LiDAR+AR technology and those made using traditional methods exhibit a similar tendency. This agrees with Zhou et al. (2019), who estimated *DBH* with MLS and obtained a fit with an R^2=0.99 and

RMSE=0.70 cm. Likewise, Heo et al. (2019) calculated with high accuracy the *TH* of urban trees (R^2=0.98 and *RMSE*=0.359 m), while the R^2 was 0.99 and the *RMSE* was 0.462 m for the *TH* of trees from a planted forest. No studies were identified in which *CD* and *CS* parameters were estimated using a mobile device (mobile LiDAR, AR, or any other sensor).

Some of the main advantages of the personal and mobile laser scanning systems proven by this study and others (Bobrowski et al., 2022; Brach et al., 2023; Çakir et al., 2021; Gollob et al., 2021; Tatsumi et al., 2021; Wang et al., 2022) are the fast scanning time, the high accuracy (*RMSE*<1 cm) and, above all, the cost of the device, as the PLS (GeoSLAM ZEB HORIZON) used by Gollob et al. (2021) costs approximately USD $50 000. Another advantage of utilizing the iPad Pro® is the availability of a wide variety of laser scanning apps for building 3D models and point clouds.

Conventional TLSs have a range of 100 to 2 000 m (Hernández, 2020; Tomaštík et al., 2017), depending on the brand; therefore, they can provide measurements for larger diameters, total heights of large trees, and various crown shapes. In contrast, the LiDAR sensor of the iPad Pro® only provides measurements for a maximum distance of 5 m. Thus, one of its main disadvantages is its limited scope, which makes it almost impossible to derive other information beyond stem position and *DBH*, as well as certain understory characteristics. However, scans with the iPad Pro® require no post-processing and are just as accurate as a TLS for measuring *DBH*, achieving an accuracy of ±1 cm according to the manufacturer (Apple Inc., 2022; Calders, 2015; Hernández, 2020). LiDAR on the iPad Pro® in combination with AR technology also works to estimate the *TH* (Kuželka et al., 2020).

The present study used this combination: the LiDAR sensor of the iPad Pro® was applied to measure the *DBH* and the respective geographic locations; this information can be of great use for competition or biodiversity models utilized in studies. Meanwhile, tree heights and crown metrics were measured using AR technology. Dai et al. (2019) used a similar combination, merging point clouds obtained with TLS and ALS to measure *TH* and crown metrics.

According to Gollob et al. (2021), Piermattei et al. (2019) and Tomaštík et al. (2017), a disadvantage of laser scanning is that the percentage of tree detection may be lower in natural forests, where the density and number of plant strata could be an issue for visualizing the height at which *DBH* is measured, due to obstructions by herbaceous plants or shrubs. In this sense, more studies should be conducted under different conditions; for example, with tropical tree species where herbaceous and shrub species are present in the understory and under conditions of high densities or steep slopes.

Comparison with other studies

Table 5 shows results from other studies that used mobile devices, LiDAR, or photogrammetry for comparison purposes. Emphasis is placed on recent research using low-cost equipment to measure forest inventory variables automatically. Various studies on the measurement of forest inventory parameters (mainly *DBH* and *TH*) using point clouds obtained with photogrammetry or LiDAR sensors are identified.

Table 5. List of studies that have used mobile devices to record tree parameters for forest inventory purposes.

Reference	Device/applied technology	No. of trees	Type of forest	Detection (%)	R^2	*RMSE* (cm)
This study	*iPad Pro®/ForestScanner®*	446	Planted Conifers	100	*DBH*=0.99 *TH*=0.98	*DBH*=0.657 *TH*=0.369

	iPad Pro®/Arboreal®			100	*CD*=0.95 *CS*=0.97	*CD*=0.341 *CS*=0.208
Guenther et al. (2024)	*iPad Pro®*	203	Natural Mixed	100	*DBH*=0.98	*DBH*=1.550
Ahamed et al. (2023)	*Smartphon e*/fotogrametría	414	Urban Mixed	100	*DBH*=0.98	*DBH*=1.550
Gülci et al. (2023)	*iPhone Pro®*	105	Mixed Planted	100	*DBH*=0.89	*DBH*=2.330
Brach et al. (2023)	*iPad Pro®/Lumentum*	776	Natural Mixed	100	*DBH*=0.990	*DBH*=5.340
Bobrowski et al. (2022)	*iPad Pro®/Abound Capture* TLS/FARO FOCUS 3D X130	100	Urban Mixed	100 100	*CBH*=0.90 *CBH*=0.91	*CBH*=7.410 *CBH*=6.510
McGlade et al. (2022)	*Azure Kinect/regular laptop single*	502	Planted Mixed			*DBH*=8.430
Wang et al. (2022)	*iPad Pro®/Zappcha*	150	Planted Conifers	90	*DBH*=0.52	*DBH*=5.200
Çakir et al. (2021)	*iPad Pro®/Forge* TLS/FARO Focus M70	62	Natural Conifers	100 100	*DBH*=0.98 *DBH*=0.99	*DBH*=0.590 *DBH*=0.560
Gollob et al. (2021)	*iPad®/3D Scanner* App *iPad®/Polycam®* *iPad®/SiteScape®* *PLS/GeoSLAM ZEB HORIZON*	424	Natural Mixed	97.33 90.65 94.68 99.52		*DBH*=3.640 *DBH*=4.510 *DBH*=3.130 *DBH*=1.590
Tatsumi et al. (2021)	*iPad Pro®/ForestScanner*	672	Natural and planted	100	*DBH*=0.96	*DBH*=2.270
Mokroš et al. (2021)	*iPad Pro®/3D Scanner App*	74	Natural Broadleaf	77.24	*DBH*=0.97	*DBH*=3.140
Liu *et al.* (2020)	*MLS/Velodyne VLP-16*	180	Urban Mixed	100	*DBH*=0.97	*DBH*=2.500
Zhou et al. (2019)	*MLS/Velodyne VLP-16*	71	Urban Broadleaf	100	*DBH*=0.99	*DBH*=0.700
Heo et al. (2019)	*MLS/SLAM*	39	Urban Broadleaf	100	*DBH*=0.91 *TH*=0.98	*DBH*=3.77 *TH*=0.359
Piermattei et al. (2019)	*CRP/Nikon®* D800 *TLS/Riegl VZ-2000*	140	Natural Mixed	84.25 93.75		*DBH*=3.090 *DBH*=1.780
Tomaštík et al. (2017)	*Tango®/Lenovo®* Phab 2 Pro multiple	118	Natural Conifers			*DBH*=1.150
	CRP/Canon® EOS 5D Mark II multiple					*DBH*=1.830
Hyyppä et al. (2018)	*Tango®/Lenovo®* Phab 2 Pro single	240	Natural Conifers			*DBH*=0.730
	Kinect/regular computer single	41				*DBH*=1.900
Bauwens et al. (2016)	MLS/ZEB1	331	Natural Mixed	91	*DBH*=0.99	*DBH*=1.110

Brouwer (2013)	*Kinect/regular laptop multiple*	150	Natural Mixed	83.75	*DBH*=1.300
	TLS/Riegl VZ-400 multiple			91.75	*DBH*.740

DBH = Diameter at breast height; *CBH* = Circumference at breast height; *TH* = Total height; *CD* = Crown diameter; *CS* = Clear-stem height.

The application of the iPad Pro® LiDAR sensor is a relatively recent method, so it can be considered novel; it has been used by Bobrowski et al. (2022), Brach et al. (2023), Çakir et al. (2021), Gollob et al. (2021), Guenther et al. (2024), Gülci et al. (2023), Mokroš et al. (2021), Tatsumi et al. (2021) and Wang et al. (2022) exclusively for measuring the *DBH*. In this study, the iPad Pro® —in Mexico, the first personal mobile device with an integrated LiDAR sensor combined with AR technology— was used to measure the parameters *DBH*, *TH*, *CS*, and *CD* relevant to forest inventories. The other studies can be grouped by the following technologies: Google Tango® (Hyyppä et al., 2018; Tomaštík et al., 2017), Microsoft Kinect® (Hyyppä et al., 2018; McGlade et al., 2022), and photogrammetry (Piermattei et al., 2019; Tomaštík et al., 2017).

The values of this study for *RMSE* in *DBH* estimation were better and similar to those obtained by Bobrowski et al. (2022), Brach et al. (2023), Çakir et al. (2021), Guenther et al. (2024) and Gülci et al. (2023), who utilized iPad Pro®, as well as those of Hyyppä et al. (2018) and Zhou et al. (2019), who used Google Tango®, Kinect®, photogrammetry, and MLS/Velodyne VLP-16, respectively (Table 5).

It should be noted that the complete set of tree parameters measured (location, *DBH*, *TH*, *CD*, and *CS*) was not estimated in the studies shown in Table 5, most of which estimated only the *DBH*. A comparative evaluation of the parameters measured by the various studies is difficult because different technologies were used for different forest structures and types.

This contribution could help to increase the use or adoption of the methodology for measurements with LiDAR and AR technology integrated into personal mobile devices, such as the iPad Pro® (or any other low-cost mobile LiDAR device), which has a high potential for operational use compared to other alternative methodologies in the inventory of planted forests.

Conclusions

The applications and workflow of the LiDAR+AR combination have been shown to require less time and personnel than conventional forest measurement tools for determining the forest parameters diameter at breast height, total height, clear-stem height, and crown diameter. This simple strategy and method can significantly reduce the costs of conducting forest inventory in planted forests.

This contribution supports the future use of the iPad Pro® LiDAR sensor for making an informed decision on how to utilize this recent remote sensing technique embedded in commercial mobile devices. Its advantages have been demonstrated: it can be applied by a single person, and the data storage is automatic and digital. Its limitations have equally been identified, and so have the configuration and applications that can be used for the inventory of forest plots or sampling sites. This novel mobile LiDAR technology on personal devices represents the next level (after TLS, MLS, and PLS technologies) toward an affordable and efficient forest inventory methodology.

Future studies should focus on evaluating the performance of mobile LiDAR on personal devices under conditions other than planted forests, such as natural tropical hardwood forests and other forest ecosystems, as well as comparison with terrestrial and airborne LiDAR devices.

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Conflict of interest

The authors declare that they have no conflict of interest.

Contribution by author

José Antonio Hernández-Moreno: data collection, registry, and analysis, preparation of graphs, and drafting of the manuscript; Diego Rafael Pérez-Salicrup: approach, follow-up of the results, revision and editing of the manuscript; Alejandro Velázquez-Martínez: follow-up of the results, revision and editing of the manuscript.

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

Apple Inc. (2022, April 11). *Store. Gift magic this holiday*. Apple store. https://www.apple.com/store

Arboreal AB. (2022, March 22). *Arboreal-Tree* (3.5) [Aplicación móvil]. Apple Store. https://apps.apple.com/us/app/arboreal-tree/id1444138299

Ayrey, E. & Hayes, D. J. (2018). The use of three-dimensional convolutional neural networks to interpret LiDAR for forest inventory. *Remote Sensing*, *10*(4), 649. https://doi.org/10.3390/rs10040649

Bauwens, S., Bartholomeus, H., Calders, K. & Lejeune, P. (2016). Forest inventory with terrestrial LiDAR: A comparison of static and hand-held mobile laser scanning. *Forests*, *7*(6), 127. https://doi.org/10.3390/f7060127

Bobrowski, R., Winczek, M., Silva, L. P., Cuchi, T., Szostak, M. & Wezyk, P. (2022). Promising uses of the iPad Pro point clouds: The case of the trunk flare diameter estimation in the urban forest. *Remote Sensing*, *14*(18), 4661. https://doi.org/10.3390/rs14184661

Brach, M., Tracz, W., Krok, G. & Gasior, J. (2023). Feasibility of low-cost lidar scanner implementation in forest sampling techniques. *Forests*, *14*(4), 706. https://doi.org/10.3390/f14040706

Brouwer, T. 2013. Low budget ranging for forest management. A microsoft kinect study [Master's Thesis, Wageningen University]. https://edepot.wur.nl/309838

Çakir, G. Y., Post, C. J., Mikhailova, E. A. & Schlautman, M. A. (2021). 3D LiDAR Scanning of urban forest structure using a consumer tablet. *Urban Science*, *5*(4), 88. https://doi.org/10.3390/urbansci5040088

Calders, K. (2015). *Terrestrial laser scanning for forest monitoring* [Doctoral's Thesis, Wageningen University]. Researchgate. https://www.researchgate.net/publication/271212221_Terrestrial_laser_scanning_for_forest_monitoring

Ciesielski, M. & Sterenczak, K. (2019). Accuracy of determining specific parameters of the urban forest using remote sensing. *iForest-Biogeosciences and Forestry*, *12*(6), 498-510. https://doi.org/10.3832/ifor3024-012

Cochran, W. G. (1977). *Sampling techniques*. John Wiley & Sons. https://fsapps.nwcg.gov/gtac/CourseDownloads/IP/Cambodia/FlashDrive/Supporting_Documentation/Cochran_1977_Sampling%20Techniques.pdf

Comisión Nacional Forestal. (2014). *Inventario Nacional Forestal y de Suelos. Procedimientos de muestreo. Versión 1.2. Muestreo 2014*. Comisión Nacional Forestal. www.conafor.gob.mx/apoyos/docs/externos/2022/DocumentosMetodologicos/2014/Anexo_procedimientos_muestreo_2014.pdf

Dai, W., Yang, B., Liang, X., Dong, Z., Huang, R., Wang, Y. & Li, W. (2019). Automated fusion of forest airborne and terrestrial point clouds through canopy density analysis. *ISPRS Journal of Photogrammetry and Remote Sensing*, *156*, 94-107. https://doi.org/10.1016/j.isprsjprs.2019.08.008

Elsherif, A., Gaulton, R. & Mills, J. (2018). Estimation of vegetation water content at leaf and canopy level using dual-wavelength commercial terrestrial laser scanners. *Interface Focus*, *8*(2), Article 29503721. https://doi.org/10.1098/rsfs.2017.0041

Estornell, J., Velázquez-Martí, A., Fernández-Sarría, A., López-Cortés, I., Martí-Gavilá J. & Salazar, D. (2017). Estimation of structural attributes of walnut trees based on terrestrial laser scanning. *Revista de Teledetección*, (48), 67-76. https://doi.org/10.4995/raet.2017.7429

Fan, Y., Feng, Z., Mannan, A., Khan, T. U., Shen, C. & Saeed, S. (2018). Estimating tree position, diameter at breast height, and tree height in real-time using a mobile Phone with RGB-D SLAM. *Remote Sensing*, *10*(11), 1845. https://doi.org/10.3390/rs10111845

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*(16), 3129. https://doi.org/10.3390/rs13163129

Guenther, M., Heenkenda, M. K., Morris, D. & Leblon, B. (2024). Tree diameter at breast height (DBH) estimation using an iPad Pro LiDAR scanner: A case study in boreal forests, Ontario, Canada. *Forests*, *15*(1), 214. https://doi.org/10.3390/f15010214

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*, Article 678. https://doi.org/10.1007/s10661-023-11366-8

Heo, H. K., Lee, D. K., Park, J. H. & Thorne, J. H. (2019). Estimating the heights and diameters at breast height of trees in an urban park and along a street using mobile LiDAR. *Landscape and Ecological Engineering*, *15*, 253-263. https://doi.org/10.1007/s11355-019-00379-6

Hernández M., J. A. (2020). *Desarrollo de un método biométrico, mediante escáner láser terrestre, aplicado a bosques mixtos, en la Reserva de la Biosfera Mariposa Monarca* [Tesis de doctorado, Colegio de Postgraduados, Campus Montecillo]. Researchgate. https://www.researchgate.net/publication/357229317_Desarrollo_de_un_metodo_biometrico_mediante_escaner_laser_terrestre_aplicado_a_bosques_mixtos_en_la_RBMM?_tp=eyJjb250ZXh0Ijp7ImZpcnN0UGFnZSI6InByb2ZpbGUiLCJwYWdlIjoicHJvZmlsZSIsInBvc2l0aW9uIjoicGFnZUNvbnRlbnQifX0

Hyyppä, J., Virtanen, J. P., Jaakkola, A., Yu, X., Hyyppä, H. & Liang, X. (2018). Feasibility of Google Tango and kinect for crowdsourcing forestry information. *Forests*, *9*(1), 6. https://doi.org/10.3390/f9010006

Infante G., S. y Zárate de L., G. P. (2012). *Métodos estadísticos: un enfoque interdisciplinario*. Editorial del Colegio de Postgraduados.

Ko, C., Lee, S., Yim, J., Kim, D. & Kang, J. (2021). Comparison of forest inventory methods at plot-level between a backpack personal laser scanning (BPLS) and conventional equipment in Jeju Island, South Korea. *Forests*, *12*(3), 308. https://doi.org/10.3390/f12030308

Kuželka, K., Slavík, M. & Surový, P. (2020). Very high-density point clouds from UAV laser scanning for automatic tree stem detection and direct diameter measurement. *Remote Sensing*, *12*(8):1236. https://doi.org/10.3390/rs12081236

Liang, X., Kukko, A., Kaartinen, H., Hyyppä, J., Yu, X., Jaakkola, A. & Wang, Y. (2014). Possibilities of a personal laser scanning system for forest mapping and ecosystem services. *Sensors*, *14*(1), 1228-1248. https://doi.org/10.3390/s140101228

Liang, X., Kankare, V., Hyyppä, J., Wang, Y., Kukko, A., Haggrén, H., Yu, X., Kaartinen, H., Jaakkola, A., Guan, F., Holopainen, M. & Vastaranta, M. (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

Liang, X., Hyyppä, J., Kaartinen, H., Lehtomäki, M., Pyörälä, J., Pfeifer, N., Holopainen, M., Brolly, G., Francesco, P., Hackenberg, J., Huang, H., Jo, H.-W., Katoh, M., Liu, L., Mokroš, M., Morel, J., Olofsson, K., Poveda-Lopez, J., Trochta, J., … & Wang, Y. (2018). International benchmarking of terrestrial laser scanning approaches for forest inventories. *ISPRS Journal of Photogrammetry and Remote Sensing*, *144*, 137-179. https://doi.org/10.1016/j.isprsjprs.2018.06.021

Liu, T., Chang, L., Niu, X. & Liu, J. (2020). Pole-like object extraction and pole-aided GNSS/IMU/LiDAR-SLAM system in urban area. *Sensors*, *20*(24), 7145. https://doi.org/10.3390/s20247145

MAPRY Co. Ltd. (2022, April 20). *ForestScanner* (1.0.2) [Aplicación móvil]. Apple store. https://apps.apple.com/bo/app/forestscanner/id1599055402

McGlade, J., Wallace, L., Reinke, K. & Jones, S. (2022). The potential of low-cost 3D imaging technologies for forestry applications: Setting a research agenda for low-cost remote sensing inventory tasks. *Forests*, *13*(2), 204. https://doi.org/10.3390/f13020204

Mokroš, M., Mikita, T., Singh, A., Tomaštík, J., Chudá, J., Wężyk, P., Kuželka, K., Surový, P., Klimánek, M., Zięba-Kulawik, K., Bobrowski, R. & Liang, X. (2021). Novel low-cost mobile mapping systems for forest inventories as terrestrial laser scanning alternatives. *International Journal of Applied Earth Observation and Geoinformatio*n, *104*, Article 102512. https://doi.org/10.1016/j.jag.2021.102512

Musálem, M. A. (2006). *Silvicultura de plantaciones forestales comerciales*. Universidad Autónoma Chapingo, División de Ciencias Forestales. https://dicifo.chapingo.mx/pdf/publicaciones/silvicultura_plantaciones_forestales_comerciales_2006.pdf

Newnham, G. J., Armston, J. D., Calders, K., Disney, M. I., Lovell, J. L., Schaaf, C. B. & Danson, F. M. (2015). Terrestrial laser scanning for plot-scale forest measurement. *Current Forestry Reports*, *1*, 239-251. https://doi.org/10.1007/s40725-015-0025-5

Piermattei, L., Karel, W., Wang, D., Wieser, M., Mokroš, M., Surový, P., Koreň, M., Tomaštík, J., Pfeifer, N. & Hollaus, M. (2019). Terrestrial structure from motion photogrammetry for deriving forest inventory data. *Remote Sensing*, *11*(8), 950. https://doi.org/10.3390/rs11080950

Ritter, T., Schwarz, M., Tockner, A., Leisch, F. & Nothdurft, A. (2017). Automatic mapping of forest stands based on three-dimensional point clouds derived from terrestrial laser-scanning. *Forests*, *8*(8), 265. https://doi.org/10.3390/f8080265

Tatsumi, S., Yamaguchi, K. & Furuya, N. (2021). ForestScanner: A mobile application for measuring and mapping trees with LiDAR-equipped iPhone and iPad. *Methods in Ecology and Evolution*, *14*(7), 1603-1609. https://doi.org/10.1101/2021.12.11.472207

Tomaštík, J., Saloň, Š., Tunák, D., Chudý, F. & Kardoš, M. (2017). Tango in forests–An initial experience of the use of the new Google technology in connection with forest inventory tasks. *Computers and Electronics in Agriculture*, *141*, 109-117. https://doi.org/10.1016/j.compag.2017.07.015

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

West, P. W. (2009). *Tree and forest measurement* (2nd Edition). Springer Berlin.

Zhou, S., Kang, F., Li, W., Kan, J., Zheng, Y. & He, G. (2019). Extracting diameter at breast height with a handheld mobile LiDAR system in an outdoor environment. *Sensors*, *19*(14), 3212. https://doi.org/10.3390/s19143212