Estimating the attributes of urban trees using terrestrial photogrammetry

Hamed Sadeghian[1], Hamed Naghavi[1*], Rahim Maleknia[1], Javad Soosani[1], Norbert Pfeifer[2]

[1] Department of Forestry, Faculty of Agricultural and Natural Resources, Lorestan University, 68151-44316 Khorramabad, Lorestan, Iran.
[2] Department of Geodesy and Geoinformation, Technische Universität Wien, Vienna, Austria.
[*] Corresponding author: Tel: +98 6633430160; Fax: +98 6633430160; E-mail: Naghavi.ha@lu.ac.ir

Abstract

Today, different methods are used to measure two-dimensional (2D) and three-dimensional (3D) attributes of trees. One of these methods, which is considered in recent years is using point clouds and a 3D model extracted from Terrestrial Photogrammetry (TP). This study aims to estimate the 2D and 3D attributes of urban trees at three levels of seedlings, single trees and sample plot using TP. Structure-from-Motion with Multi-View Stereo-photogrammetry (SfM-MVS) method was used to derive the point clouds and the 3D model. Comparing estimated values of diameter at the middle of trunk of seedlings and diameter at breast height (DBH) of trees, using TP with measured values showed that the values of RMSE% were < 2% at three levels of seedlings, single trees and sample plot. Furthermore, validation of the estimated values of total height and crown height attributes of seedlings and trees at three levels showed that the RMSE% did not exceed 4% and 5%, respectively. Considering the overlap of tree crowns with each other in the sample plot, the average diameter of the crown attribute was estimated only in seedlings and single tree levels with RMSE%= 6.51% and 9.34%, respectively. The validation of estimated values of stem volume of seedlings and trees at three levels showed that the lowest errors were returned from trees within a sample plot with RMSE%=14.37%, whereas the highest rates of errors were achieved for seedlings with RMSE%= 20.99%. As an alternative to approaches such as employing laser scanners, this method is quick, inexpensive, non-destructive, and does not need specialized equipment.

Keywords: Point clouds, 3D model, SfM-MVS, Sample plot, Urban greening

Introduction

According to United Nation's prediction, the urban populations will increase from around 47% in 2010 to 60% by 2030 (United Nation, 2020; Van Delm and Gulinck, 2011). This increase in population and subsequent increase in the size of urban areas have led to green space and urban trees to be in the focus of researchers and city managers due to their key role to provide direct and indirect ecosystem services such as biodiversity protection, carbon sequestration, reducing air pollution, preventing the formation of thermal islands, maintaining urban aesthetics, recreational value, reduction of noise pollution, preservation of wildlife habitat, improving environmental quality and reducing storm water (Bolund and Hunhammar, 1999; Matyieu and Aryal, 2005; Holopainen et al., 2013; Morgenroth and Gomez, 2014; Lee et al., 2016; Wolf et al., 2020; Song et al., 2020; Gülçin and Konijnendijk van den Bosch, 2021). It was proven that the access to accurate and up to date information on tree attributes, such as DBH, height, crown dimension, basal area, stem volume and aboveground biomass help managers, researchers, governments and environmental organizations for planning and preservation, biophysical process modelling, ecosystem services assessment and quantifying the economic value of the urban greening (Matyieu and Aryal, 2005; Nowak et al., 2008; Morgenroth and Gomez, 2014; Nielsen et al., 2014; Miller et al., 2105; Lee et al., 2016; Mikita et al., 2016; Mokroš et al., 2018).

To assess tree attributes, traditional inventory techniques often employ mechanical or optical equipment. However, using these methods is time consuming and expensive, and they do not have the capacity to directly assess tree attributes like volume and biomass (Marzulii et al., 2020). Using allometric equations is one of the methods of estimating the attributes of trees, and estimating 3D attributes with this method is usually associated with error in terms of the different morphology of trees (Marzulli et al., 2020). Therefore, studies were conducted over the last several decades to develop replacements for conventional inventory techniques. Using point clouds data to generate the 3D structure of trees is one of these techniques. Using magnetic motion trackers, laser scanners, or photogrammetric techniques, one may build the 3D structure of trees (Surový et al., 2016; Mokroš et al., 2020).

Using a magnetic motion tracker is usually time consuming, since this device must move near a tree trunk, and it will usually be difficult to measure the attributes of trees at upper part of the trunk (Mokroš et al., 2020). Regarding the ability of terrestrial laser scanning (TLS) to accurately estimate trees attributes, many researchers have estimated the 2D and 3D attributes of trees, such as DBH, height, crown attributes, aboveground biomass and volume using TLS so far (Moorthy et al., 2011; Moskal and Zheng, 2012; Kankare et al., 2013; Liu et al., 2018; Giannetti et al., 2018). Despite the advantages of TLS, the use of these systems has limitations such as high cost, the requirement for a professional operator and difficulty to move equipment during the inventory (Mikita et al., 2016; Liang et al., 2016; Marzulii et al., 2020). Therefore, by considering the advances in image matching algorithms, cameras and computer hardware, photogrammetry can be considered a cost-effective alternative to laser scanning in the point clouds generation and 3D structures of the trees (Roberts et al., 2019; Akpo et al., 2021).

The close-range photogrammetry (CRP) is considered as one of the sub-categories of photogrammetric methods. Hence, the distance of the object from the camera is usually less than 300 meters (Luhmann et al., 2010), and the images can be captured in terrestrial or aerial states.

Different methods can be used to derive 3D models; one of which being SfM-MVS method (commonly abbreviated to SfM) (Iglhaut et al., 2019). This method was introduced by Ullman in 1979 and later expanded as a low-cost and fast method for making 3D models (Ullman, 1979; Morgenroth and Gomez, 2014; Iglhaut et al., 2019). In this method, overlapping 2D images are taken from different points and angles of view of the object, and are then converted into 3D models (Morgenroth and Gomez, 2014; Miller et al., 2015; Mikita et al., 2016; Marzulii et al., 2020).

So far, researchers have conducted various studies on the application of 3D models in estimating different 2D and 3D tree attributes. For example, Sakai et al., (2021) estimated the height, crown diameter and stump diameter of 10 sample plots using the SfM method. R^2 values were 0.81, 0.89 and 0.94 for stump diameter, canopy height and tree height, respectively. Mokroš et al., (2020) used SfM to estimate the annual trunk increments of trees of different species. Comparing estimated perimeters from SfM method with the measured values showed that the RMSE% did not exceed 1% for all tree species. Marzulli et al., (2020) estimated the DBH and stem volume of trees in a sample plot using images taken by a smartphone and the SfM method. The comparison among 3D models and field data showed the RMSE of 1.9 cm and 0.094 m^3, for DBH and volume, respectively. Miller et al., (2015) estimated the 2D and 3D attributes of 30 small potted trees using handheld camera images and SfM-MVS method. They reported RMSE% of 3.74%, 11.93%, 9.6% and 14.76% when estimating the height, crown height, diameter and crown spread using SfM-MVS method, respectively. Besides, Morgenroth and Gomez (2014) concluded that the SfM-MVS method could estimate the diameter of trees with RMSE%= 3.7% as well as height with RMSE%= 2.59% by examining one potted seedling and 2 mature trees. Other studies such as Liang et al., (2014); Forsman et al., (2016); Mikita et al., (2016); Surový et al., (2016); Mokroš et al., (2018); Piermattei et al., (2019); Mulverhill et al., (2020) and Bayati et al., (2021) have also surveyed the application of TP method in estimating different attributes at the single tree, sample plot and stand levels. These tests revealed that the approach employed in calculating 2D and 3D tree attributes might be an accurate, rapid, low-cost, and non-destructive method. Most of research mentioned in the literature review were done in forests, while several studies were conducted in urban greening, so that 2D and 3D models have been developed only for small potted seedlings and single mature trees. Thus, this study aimed to estimate the 2D and 3D attributes of 74 trees of different species at three levels of seedlings, single trees and trees within the sample plot in urban greening using TP and SfM-MVS methods. Moreover, this research seeks to answer these questions: i) As an alternative to TLS, can the TP and SfM-MVS approaches estimate the 2D and 3D features of urban trees at the seedling, individual tree, and sample plot levels? ii) Does the diminutive size of seedlings relative to mature trees impact the accuracy of calculating their 2D and 3D attributes?

Materials and methods

Materials

The measurements of trees were performed at three levels, including 30 seedlings, 30 single trees and 14 trees located in a sample plot with dimensions of 28 × 11 meters. Seedlings were selected from urban nurseries and other trees were selected from trees planted in urban green space of Khorramabad and the Faculty of Agriculture and Natural Resources of Lorestan University. Khorramabad is the capital of Lorestan province and with an area of 46.94 km^2 (33°25´38" to 33° 35´52" N and 48° 18´ 29" to 48° 23´ 39" E) in the southwest of Iran. The list of different coniferous and broadleaves species studied in this research is presented in Table. 1.

Table. 1. List of species examined in the present study

Level	Scientific name	Number
Seedlings	*Thuja orientalis*	5
	Chamaecyparis lawsoniana	5
	Pinus brutia	5
	Laurus nobilis	5
	Populus alba	5
	Ailanthus altissima	3
	Fraxinus excelsior	2
Single trees	*Pinus eldarica*	12
	Cupressus arizonica	3
	Melia azedarach	5
	Robinia pseudoacacia	8
	Fraxinus excelsior	2
Sample plot	*Pinus eldarica*	14

Methods

Reference data measurement

2D attributes

2D attributes, including diameter, height, crown height and average diameter of the crown of seedlings and trees at three levels were measured. Regarding small size of the seedlings, the diameter at mid-height of trunk was measured instead of the DBH. The DBH of mature trees and diameter at mid-height of trunk of seedlings were measured using a caliper.

The total height and crown height of seedlings were measured using a measuring tape and these attributes were measured using TruPulse 360 Laser Rangefinder at single trees and sample plot levels.

The crown diameter of seedlings and trees was measured using a measuring tape in two perpendicular directions, and the average crown diameter of each seedling or tree was computed using the average of the measured diameters. Because of the closeness of trees and the overlap of tree crowns, it was impossible to compare each tree's crown diameter to the values calculated in the sample plot (no separation in the acquired images).

3D attributes

Seedling volume was measured using Xylometry (Miller et al. 2015), in which the seedlings were cut and divided into small pieces after the photogrammetric imaging. Then, the pieces related to different parts of each seedling were separated, numbered, and packaged. The wooden sections were submerged in water for 48 hours to saturate and prevent them from absorbing water. Finally, the volume of each piece was estimated by inserting it in a graduated cylinder filled halfway with water and measuring the variations in water volume. To accurately calculate the volume of plots, the volume of plastic strips used for packing was calculated separately and the volume of pieces was reduced (Miller et al., 2015).

Given the impossibility of cutting the trees, the Smalian formula was used to estimate the tree's stem volume based on the morphology of the tree stems (Ahmad et al., 2020). To more accurately estimate the stem volume, the stem length was divided into 65 cm sections using a measuring tape. The total stem volume of each tree was calculated using Equation 1(Ahmad et al., 2020).

Equation. 1. $$V = \sum_{i=1}^{i=n}(\pi \times (\frac{d_{base}^2 + d_{top}^2}{8}) \times h_i)$$

Where V represents the stem volume of each tree (cm^3), h_i denotes the length of each plot of tree stem (cm), d_{base} is the initial diameter of each section of tree stem (cm), d_{top} represents the final diameter of each section of tree stem (cm), π = 3.14 and n: is the number of sections of each stem.

The value of tree crown volume was not compared with the values obtained from TP at single trees and sample plot levels, in terms of the inability to accurately measure the volume of tree crowns in terrestrial measurements.

The mean values of measured attributes of seedlings and trees at each of the three levels are presented in Fig.1.

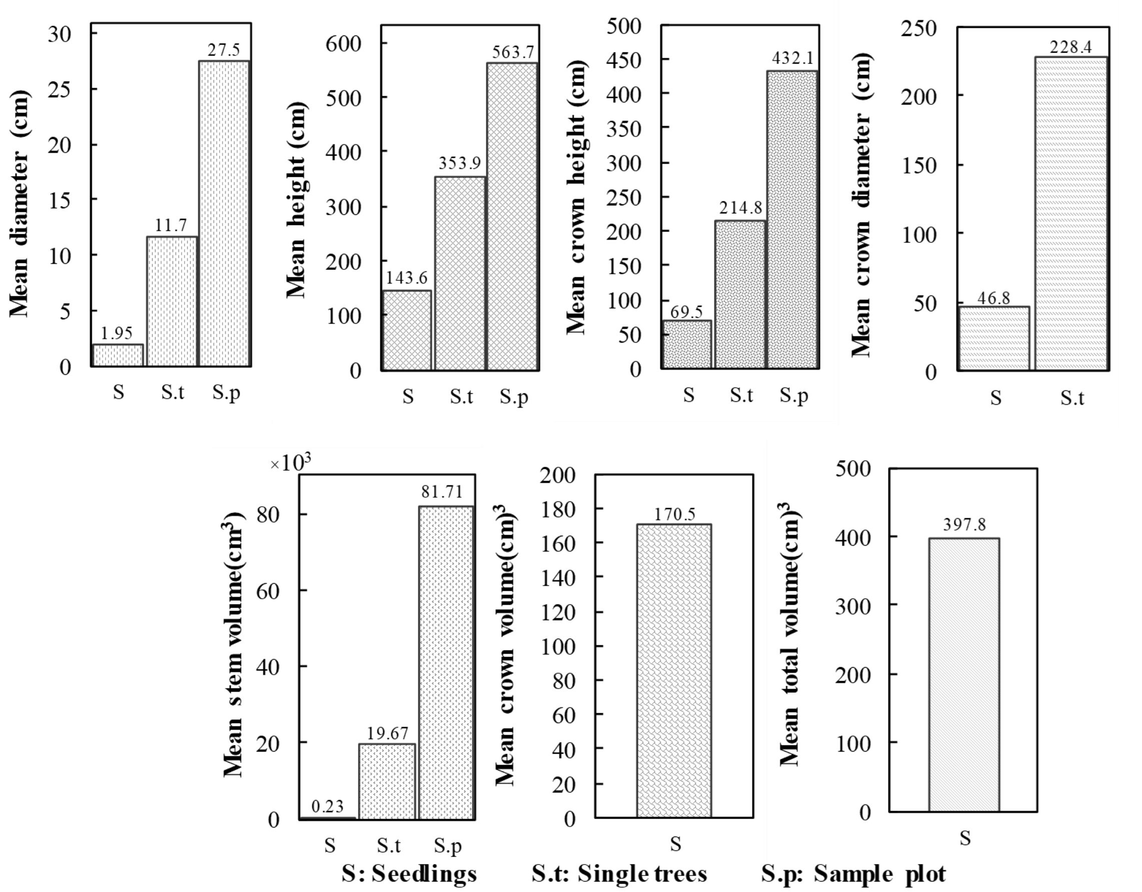

Fig. 1. The mean value of the measured attributes of seedlings and trees

Image Acquisition

Images were captured using a Canon EOS 700D semi-professional camera equipped with a 30 mm EF-S lens. To maintain the camera's stability during shooting, the camera was placed on a tripod with adjustable height. In order to increase the quality of the images, the photos were taken using manual settings (shutter speed= 1/180 second, F= 4.5 aperture and ISO= automatic). The approach suggested by Morgenroth and Gomez (2014) and Miller et al., (2015) was used to photograph seedlings and single trees. Therefore, two concentric rings were painted around the trees. Then, photographs of trees were taken around the circumferences of these circles at regular intervals. The distances among the shooting points were determined so that the overlap of each image with the next one is > 50%. Scale is needed in the images to create a 3D model in the software environment, therefore, a box with specified dimensions was used when photographing seedlings, while a levelling staff with a height of 3 meters was used during photography of single mature trees. Therefore, after preliminary studies, a combination of the methods proposed by Mokroš et al., (2018) was used in order to obtain the best method of photographing trees in the sample plot. In order to ensure sufficient overlap among the images, photos were taken in different directions, including the perimeter and the two diameters of the sample plot. The distance between the photogrammetric points was approximately 2.5 meters, whereas the overlap between the images was at least 50%. Therefore, the distance among the photogrammetric points of the trees was between 1 and 3 meters, depending on the height of the trees, which in most cases was about 2.5 meters. During imaging, 5 levelling staffs were placed at the four corners and the center of the sample plot to define the scale during image processing.

Image processing

We used Photoscan-professional software for the reconstruction of 3D models (Agisoft LLC, Saint Petersburg, Russia) (Morgenroth and Gomez, 2014). To derive a 3D model of seedlings and trees using the SfM-MVS method, the position and attributes of the camera and sparse point clouds were required to be first derived using SfM method (James and Robson, 2012; Miller et al., 2015; Mokroš et al., 2018; Iglhaut et al., 2019). For this purpose, the images were loaded and aligned in the software. Then, the key points were extracted from the overlapping of the images and converted to tie points after matching (Mokroš et al., 2018). The software default values were set to 40000 and 4000 to define the maximum number of key points and tie points, respectively. Using dense image matching methods and the MVS approach, the sparse point clouds retrieved in the previous phase were transformed to dense point clouds in the subsequent step (James and Robson, 2012; Iglhaut et al., 2019). The MVS technique transforms sparse point clouds into dense point clouds by eliminating noisy data and multiplying reconstructed points (Iglhaut et al., 2019). This helps more accurately estimating the 2D and 3D attributes of trees. Finally, the mesh model of each seedling and tree was produced using a dense point clouds. Afterwards, 2D and 3D attributes of seedlings or trees were measured (Miller et al., 2015). To estimate the 3D attributes, unrelated elements such as pots and ground surface were removed in each model, and the 3D attributes were measured separately. An example of a 3D model produced for seedlings and trees is shown in Fig. 2 and Online Resources 1 and 2.

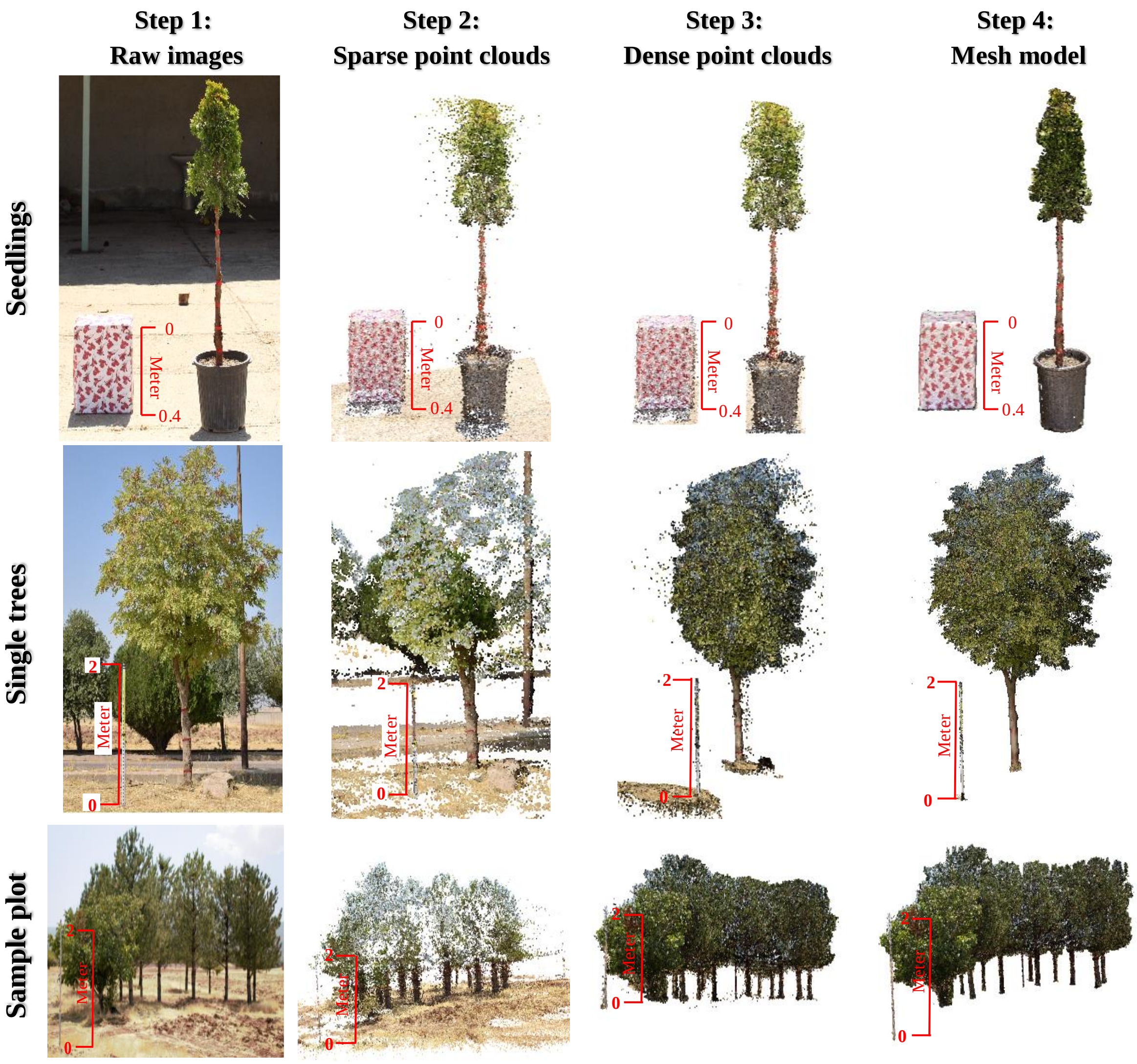

Fig. 2. Different stages of developing a 3D model of seedlings and trees a) raw images, b) sparse point clouds, c) dense point clouds and d) mesh model

Statistical Analysis

To compare the estimated and reference data, statistics of coefficient of determination (R^2) (Hobart et al., 2020), Root Mean Square Error (RMSE), Root Mean Square Percentage Error (RMSE %), Bias, relative Bias % (Roberts et al., 2019), Mean Absolute Error (MAE) and Mean Absolute Percentage Error (MAE%) (Liu and Zhang, 2018) were used (Table. 2). All relationships and statistical graphs were processed in SPSS statistics 25 IBM and Microsoft Excel 2016 software. The flowchart of the research steps is presented in Fig. 3.

Table. 2. Statistics formula used to compare estimated and measured data

Name	Equation
Coefficient of determination	$R^2 = \frac{\frac{1}{n}\sum_{i=1}^{n}(y_i - \bar{y})(\hat{y}_i - \bar{\hat{y}})}{\sqrt{(\frac{1}{n}\sum_{i=1}^{n}(y_i - \bar{y})^2)(\frac{1}{n}\sum_{i=1}^{n}(\hat{y}_i - \bar{\hat{y}})^2)}}$
Root Mean Square Error	$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n}}$
Root Mean Square Percentage Error	$\text{RMSE\%} = \frac{RMSE}{\left(\frac{\sum_{i=1}^{n}\hat{y}_i}{n}\right)} \times 100$
Bias	$\text{Bias} = \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)}{n}$
Percent Bias	$\text{Bias\%} = \frac{Bias}{\left(\frac{\sum_{i=1}^{n}\hat{y}_i}{n}\right)} \times 100$
Mean Absolute Error	$\text{MAE} = \frac{1}{n}\sum_{i=1}^{n}\lvert y_i - \hat{y}_i \rvert$
Mean Absolute Percentage Error	$\text{MAE\%} = \frac{1}{n}\sum_{i=1}^{n}\left\lvert \frac{y_i - \hat{y}_i}{\hat{y}_i} \right\rvert \times 100$

In the above equations, $\hat{y}_i$ =measured values, y_i= estimated values and n= number of trees or seedlings.

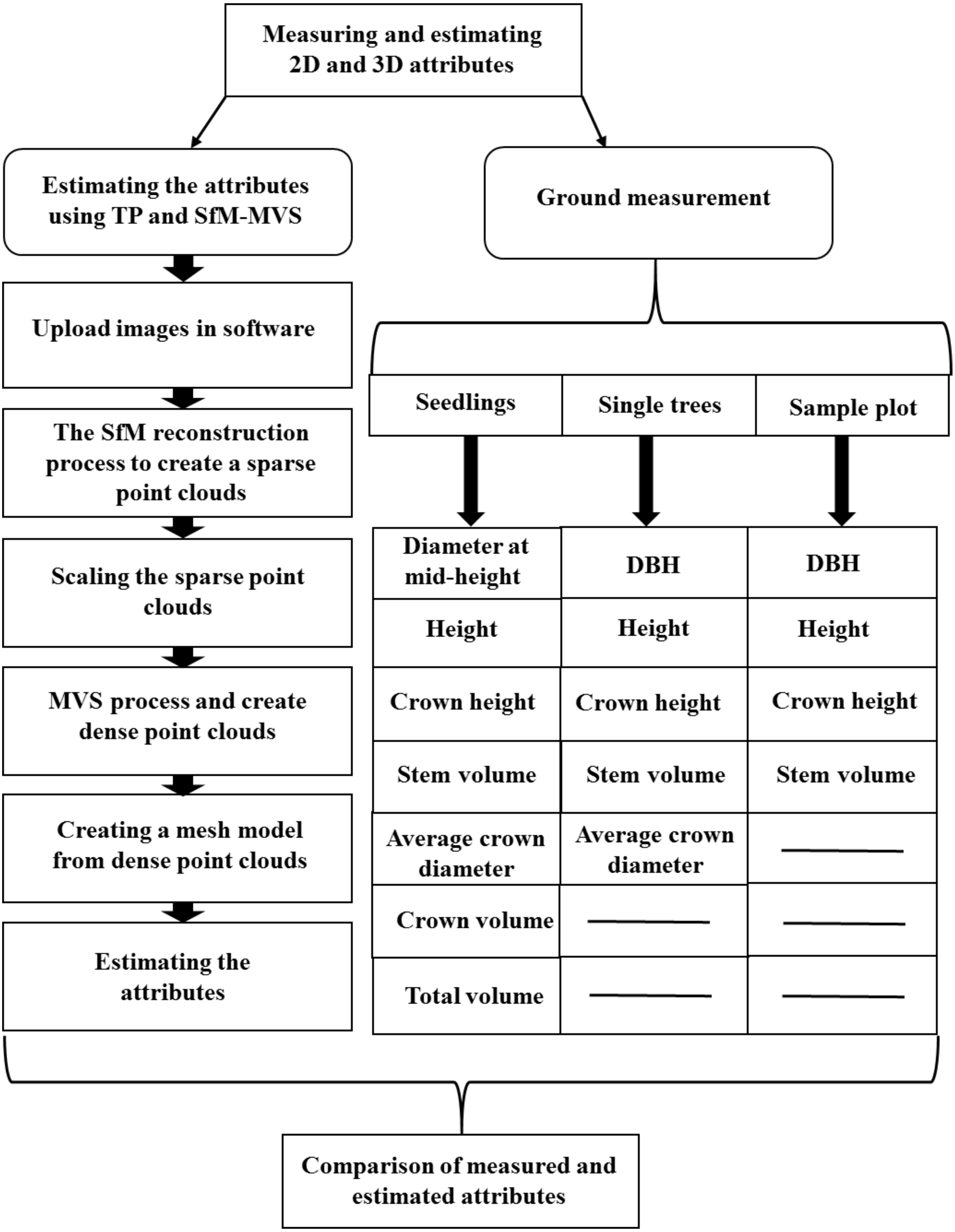

Fig. 3. Flowchart of the study

221

Results

Comparison of estimated and measured 2D and 3D attributes of seedlings

Comparing estimated values of 2D attributes of seedlings using TP with values measured in the laboratory showed that the values of RMSE%, Bias% and MAE% for all estimated 2D attributes were < 7%, which indicated high accuracy to estimate the 2D attributes of seedlings. Among 2D attributes, diameter at the middle height of trunk and average crown diameter showed the lowest and highest RMSE% with 1.16% and 6.51%, respectively (Table. 3). Moreover, the scatter plots of estimated and reference values showed a high correlation, suggesting R^2 of 0.99, 0.98, 0.98 and 0.98 for diameter at middle height of the stem, total height, crown height and average diameter of the crown of the seedlings, respectively (Fig. 4).

Table. 3. Statistics related to comparing estimated and measured 2D attributes of seedlings

Attributes	n	RMSE	RMSE%	Bias	Bias%	MAE	MAE%
Diameter (cm)	30	0.02	1.16	-0.01	-0.70	0.01	1
Height (cm)	30	4.22	2.94	1.20	0.83	1.22	1.11
Crown height (cm)	30	1.96	2.82	0.77	1.11	0.77	1.30
Average crown diameter (cm)	30	3.04	6.51	-0.06	-0.12	1.88	5.01

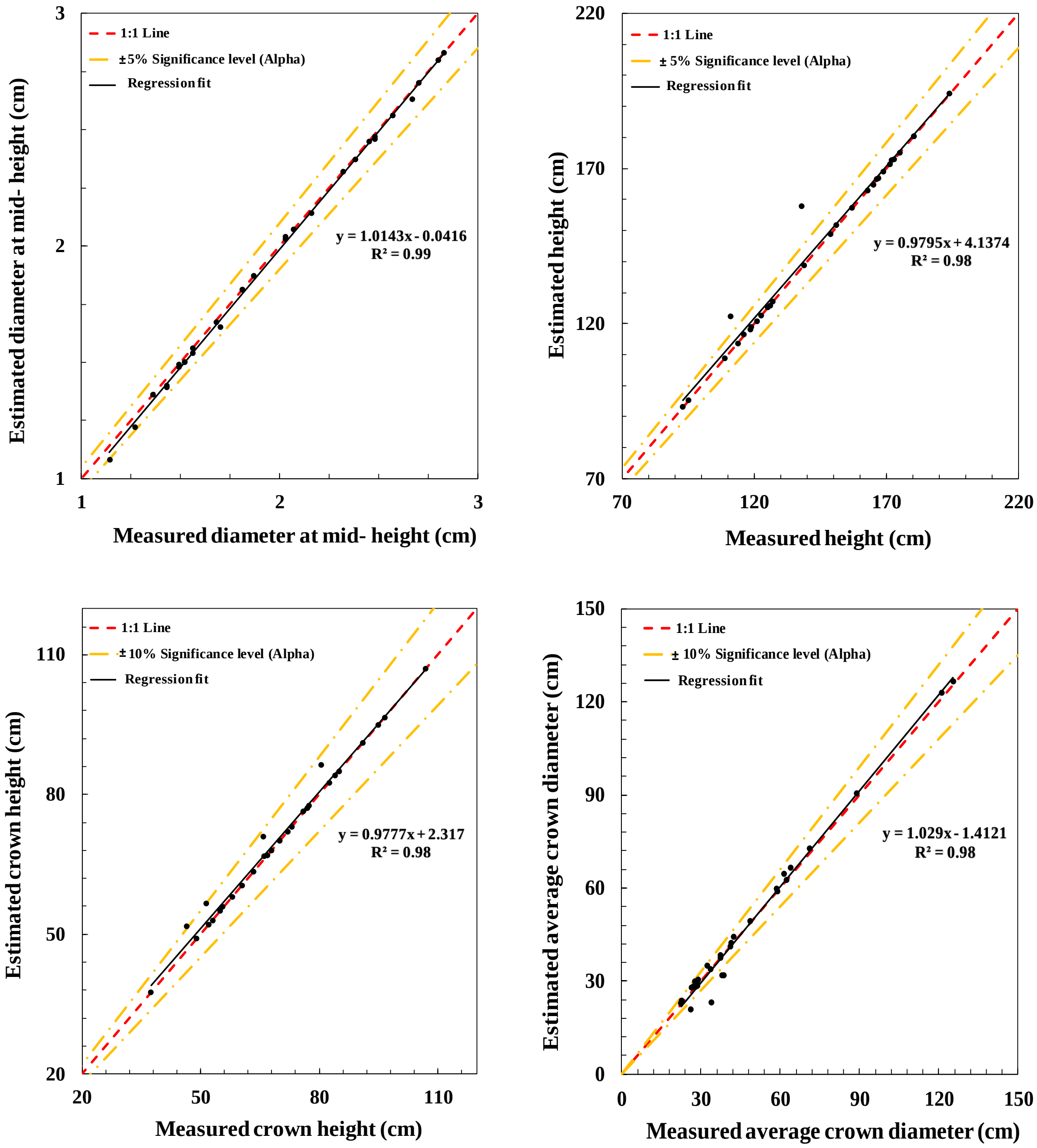

Fig. 4. Scatter plot between estimated and measured values of 2D attributes of seedlings

The validation of estimated values of 3D attributes of seedlings showed that the lowest RMSE%, Bias% and MAE% were returned for stem volume (20.99%, -14.96% and 14.83%, respectively), whereas the highest rates were achieved for crown volume (30.85%, -18.40% and 15.42%, respectively) (Table. 4). R^2 values for the stem volume, crown volume and total volume attributes were 0.90, 0.82 and 0.88, respectively (Fig. 5).

Table. 4. Statistics related to the comparison of estimated and measured 3D attributes of seedlings

Attributes	n	RMSE	RMSE%	Bias	Bias%	MAE	MAE%
Stem volume (cm^3)	30	47.72	20.99	-34	-14.96	65.37	14.83
Crown volume (cm^3)	30	52.60	30.85	-31.36	-18.40	34	15.42
Total volume (cm^3)	30	97.33	24.46	-65.37	-16.43	31.36	14.86

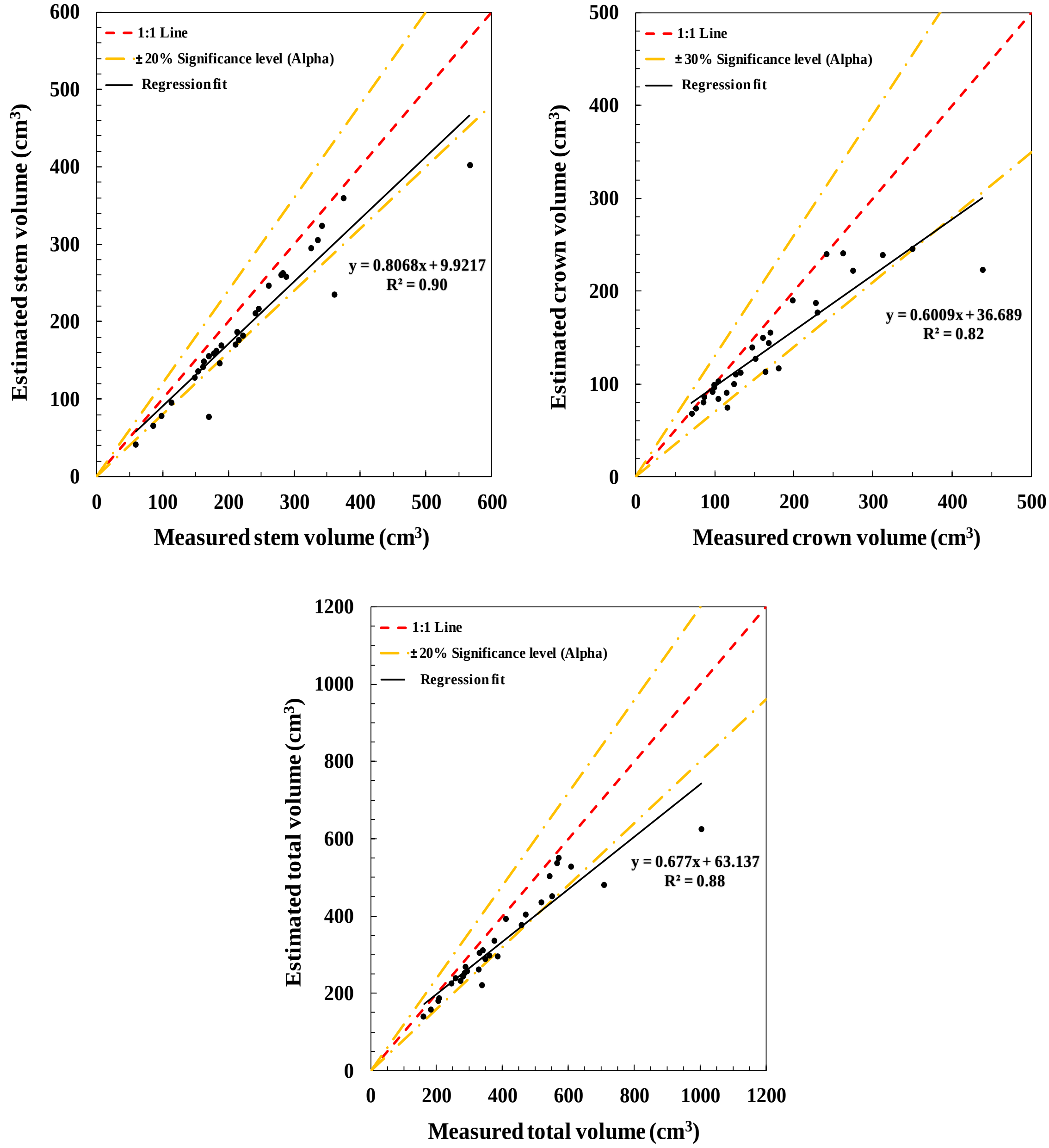

Fig. 5. Scatter plot between estimated and measured values of 3D attributes of seedlings

Comparison of estimated and measured 2D and 3D attributes of single trees

Comparison of the estimated values of single tree attributes with reference values showed that 2D attributes were estimated more accurately than 3D attributes. Among all attributes, the lowest RMSE%, and MAE% were returned for DBH (1.02% and 0.55%, respectively). Whereas, the stem volume with RMSE%= 17.69% and MAE%= 12.03%, showed the lowest accuracy (Table. 5). The scatter plot of the estimated and reference values for 2D and 3D tree attributes suggested R^2 values of 0.99, 0.99, 0.98, 0.97 and 0.97 for DBH, total height, crown height, average crown diameter and stem volume of single trees, respectively (Fig. 6).

Table. 5. Statistics on comparing estimated 2D and 3D attributes and measured values of single trees

Attributes	n	RMSE	RMSE%	Bias	Bias%	MAE	MAE%
DBH (cm)	30	0.12	1.02	-0.05	-0.43	0.05	0.55
Height (cm)	30	5.81	1.64	3.06	0.87	3.06	0.91
Crown height (cm)	30	6.55	3.05	2	0.93	3.33	1.51
Average crown diameter (cm)	30	21.34	9.34	17.8	7.80	18.66	9.26
Stem volume (cm^3)	30	3.47	17.69	0.96	4.90	1.96	12.03

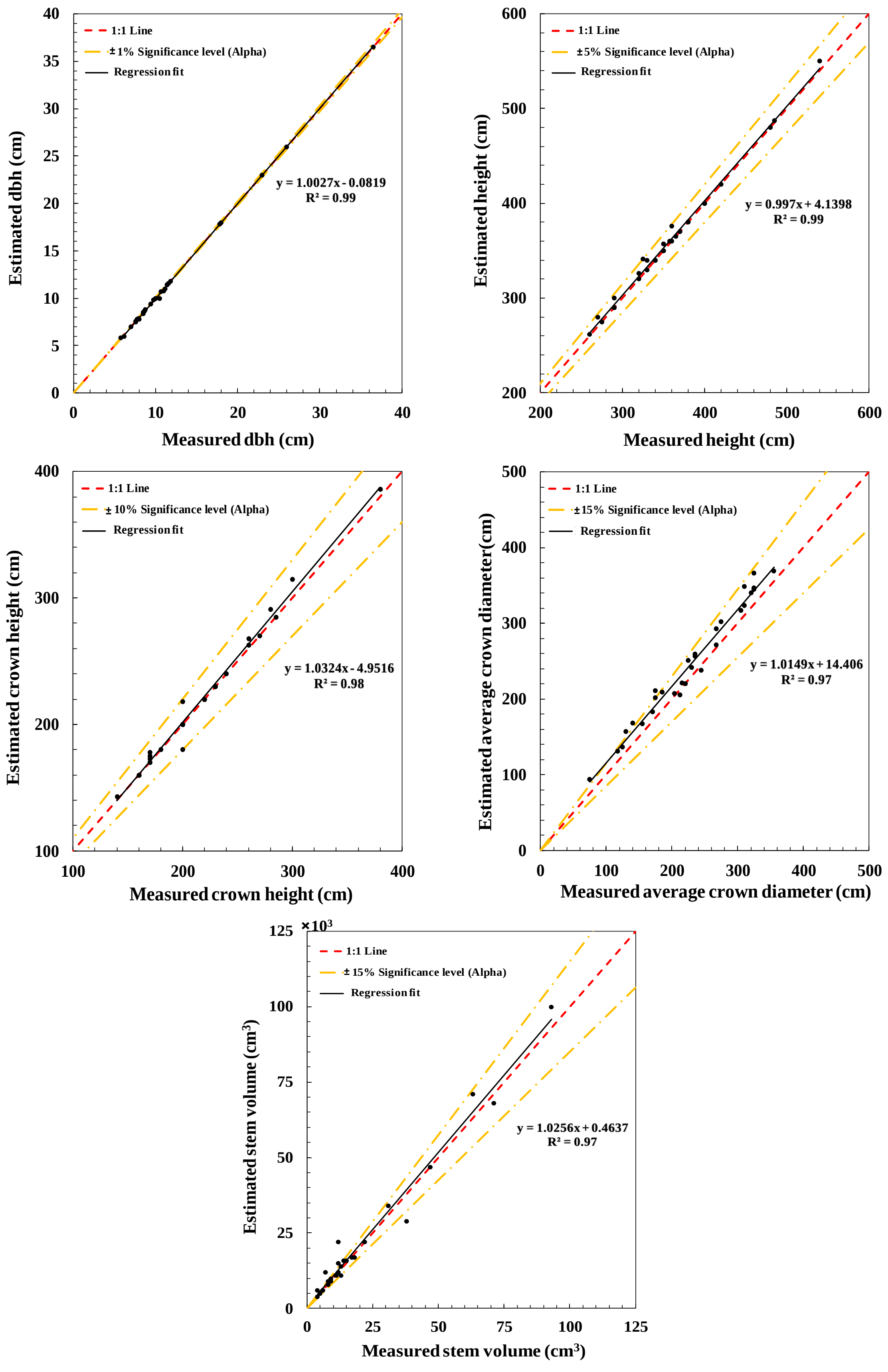

Fig. 6. Scatter plot of estimated and measured values of single trees

Comparison of estimated and measured 2D and 3D attributes of trees at sample plot level

The validation results of estimated DBH, crown height, stem volume of trees in the sample plot are shown in Table. 6 and Fig. 7. Among all attributes, tree DBH showed the lowest error rate (RMSE% = 1.72% and MAE% = 1.39%) and tree stem volume returned highest error rate (RMSE% and MAE% of 14.37% and 15.40%, respectively). Further, the bias% values of all 2D and 3D attributes were < 5%. The calculated R^2 suggested a high correlation between the estimated and the reference 2D and 3D attributes (Fig. 7).

Table. 6. Statistics related to comparison of the estimated and measured values of the attributes of the trees within the sample plot

attributes	n	RMSE	RMSE%	Bias	Bias%	MAE	MAE%
DBH (cm)	14	0.47	1.72	-0.25	-0.91	0.35	1.39
Height (cm)	14	20.54	3.64	19.5	3.46	19.5	3.47
Crown height (cm)	14	20.54	4.75	19.5	4.50	19.5	4.52
Stem volume (cm^3)	14	11.74	14.37	2.57	3.15	9.14	15.40

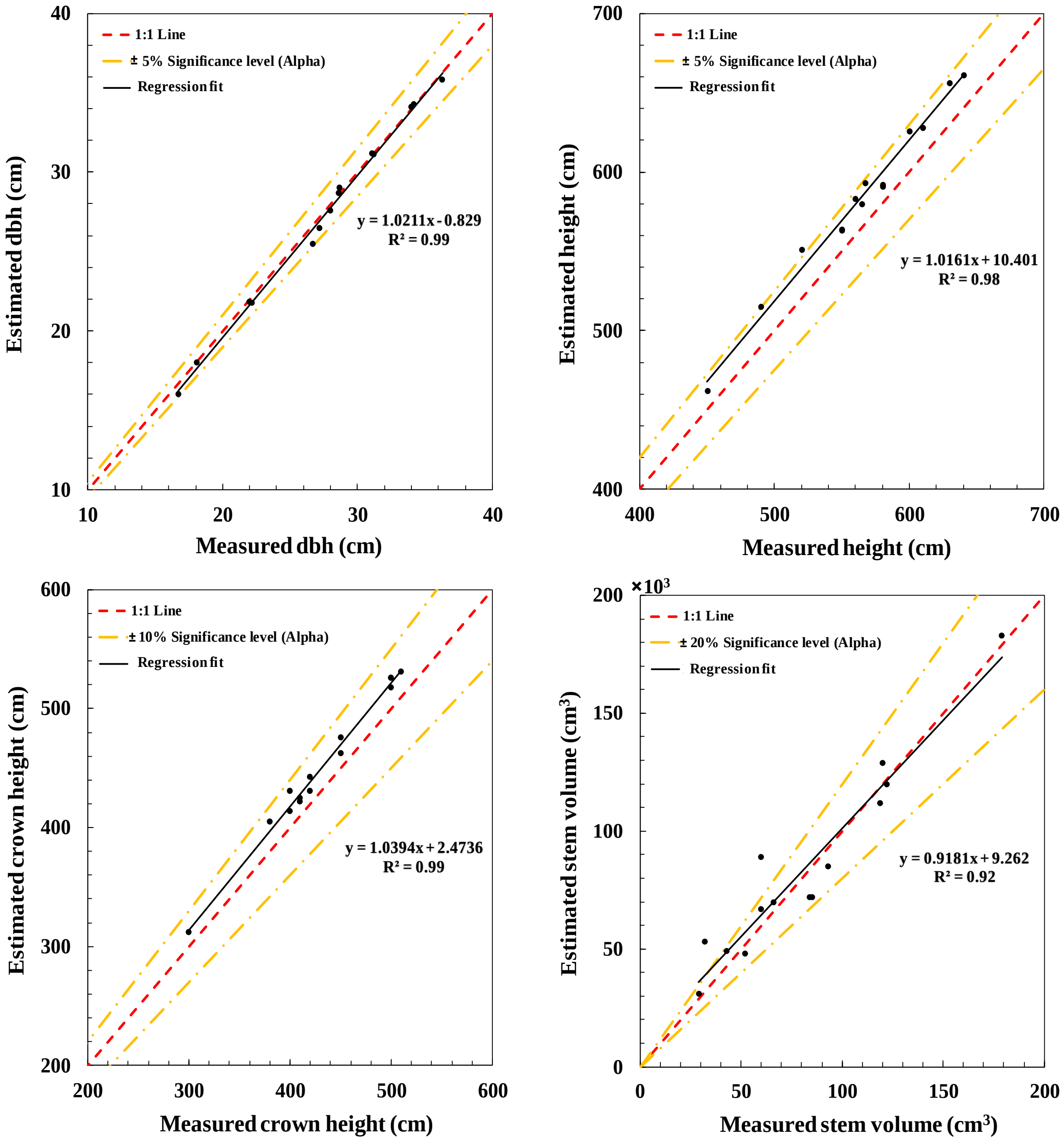

Fig. 7. Scatter plot of the estimated and measured values of trees attributes in the sample plot

Comparison of estimated and measured 2D and 3D attributes at three levels

Comparing estimated values of diameter at the middle height of trunk of seedlings and DBH of trees using TP with measured values showed that the values of RMSE%, Bias% and MAE%, were < 2% at all three levels. The height of single trees and trees within a sample plot were calculated using the lowest and highest RMSE% among the three levels (1.64% and 3.64%, respectively). However, the crown height of seedlings was assessed with more precision than the other two levels. Considering the overlap of tree crowns with each other in sample plot, the average diameter of the crown attribute was estimated in seedlings and single trees with RMSE%= 6.51% and 9.34%, respectively. The validation of estimated stem volume of seedlings and trees at three levels revealed that trees within a sample plot had the lowest RMSE% and Bias% (14.37% and 3.15%, respectively), but seedlings had the highest rates (20.99% and -14.96%, respectively) (Tables. 3-6).

Discussion

Considering the issues such as population growth, development of urban areas and climate change, sustainable management of urban greening has nowadays increasingly become important in terms of its role to increase the physical and mental health of urban inhabitants. Since the basis of urban sustainable management since access to accurate and up-to-date information is considered as a basis for urban sustainable management, this study aimed to use TP and SfM-MVS methods in estimating 2D and 3D attributes of urban trees at three different levels of seedling, single trees and trees within a sample plot.

Estimation of 2D and 3D attributes of seedlings using TP

Comparing estimated and lab-measured 2D attributes of seedlings using TP and SfM-MVS method suggested high accuracy of estimating the 2D attributes of seedlings. The results of both studies of Miller et al., (2015) and Morgenroth and Gomez (2014) were in line with the results of our research and showed the high accuracy of SfM-MVS method in estimating the 2D seedling attributes.

When estimating the 3D attributes of seedlings, results showed lower accuracy compared with the 2D attributes. However, the stem volume was more accurately estimate than crown volume. Considering the irregular shape of the tree crown and the empty space between the foliage of the seedlings, the estimated crown volume was different from the actual volume calculated through immersion. Furthermore, since the total volume of each seedling was determined from the total stem and crown volumes, this difference had an impact on the predicted total volume. Due to the narrow diameter of the seedlings, particularly in the region linking the stem to the crown, the volume associated to the terminal parts of the stem was calculated with a minor discrepancy. Among few studies conducted to estimate the volume of seedlings using TP, Miller et al., (2015) can be referred to, in which RMSE% and Bias% of 12.33% and -8.2% were reported for stem volume, while -18.53% and -5.56%, were reported for total volume of seedlings, respectively. Finally, in line with the results of our study, they concluded that the accuracy of the TP to estimate 2D attributes is higher those achieved for 3D attributes.

Estimation of 2D and 3D attributes of single trees using TP

RMSE%, Bias% and MAE% values obtained when estimating the 2D tree attributes including DBH, average crown diameter, crown height and height showed that our approach was capable to produce high accuracies. In this regard, Sakai et al., (2021) reported the R^2 values of 0.94, 0.89, 0.81 as well as the RMSEs of 0.13 m, 0.33 m and 0.89 cm for estimating the height, crown diameter and stump diameter of trees using TP, respectively. In addition, the results obtained by Bayati et al., (2021) in evaluating the performance of SfM-MVS method in estimating the tree attributes showed $R^2 = 0.98$ for DBH and $R^2 = 0.89$ for tree height. Roberts et al., (2019) estimated the DBH of single urban trees using TP with a RMSE of 10.37%. Results from those previous studies were in line with the results of this study in estimating the 2D tree attributes.

Comparing stem volume of the by TP and the SfM-MVS method with the volume calculated by the Smalian formula showed relatively high accuracy of our method in estimating the volumetric attributes of single trees. One of the reasons for the lower stem volume estimate accuracy relative to other features seems to be the impossibility of cutting trees, i.e. precise field-based stem volume measurement. To resolve this problem, it was attempted to measure the stem volume within smaller tree sections. However, using formulas which assume the stem shape as cylindrical is associated with drawbacks for different species. Tamaki et al. (2019) pointed out that TP and SfM-MVS methods have the ability and high accuracy in estimating the stem volume of trees. Mulverhill et al. (2019) also stated that there is no significant difference between the stem volume of single trees estimated by TP method and those calculated by allometric equations.

Estimation of 2D and 3D attributes of trees within the sample plot using TP

In the third part of this study, we examined the efficiency of 3D models using TP along with the use of SfM-MVS method to estimate the 2D and 3D attributes of trees at the sample plot level. Due to the overlap of tree crowns with each other and the inability of identifying the precise range of tree crowns, it was not able to estimate the crown spread of each tree, as specified in the Methods section. As a result, the DBH of trees was the most accurate attribute of trees assessed using 3D models. The results showed that the stem volume of trees was estimated with RMSE%= 14.37%. Comparing estimated stem volume of trees at tree and plot levels suggested that the accuracy was slightly higher at the sample plot level. This was because the trees within the sample plot were entirely from the same species and with an almost "cylindrical" stem shape. However, at the single tree level, tree species were different and thus were associated with different stem shapes. In this regard, previous studies using TP at sample plot and stand levels like Mikita et al., (2016) in estimating the attributes of DBH, height and volume of trees, Forsman et al., (2016), Mokroš et al., (2018), Piermattei et al., (2019) in estimating the DBH, Marzulli et al., (2020) in estimating the DBH and stem volume, Sakai et al., (2021) in estimating the height, crown width and diameter of the tree stumps suggested that the TP method was relatively accurate to estimate the mentioned attributes at the sample plot level. However, they showed slightly different accuracies in predicting DBH, height, and stem volume attributes than we did, which might be because the majority of the researches were done in natural forests. Besides, factors such as photogrammetric method, stand conditions, species type, tree dimensions, tree density, physiographic conditions and floor and shrub coverage can partly influence the results.

The potentials of workflow for practical implementation

2D and 3D attributes of seedlings and trees were estimated using TP and SfM-MVS methods. According to the results, this method can be suggested as a fast, low-cost and non-destructive method that provides accurate estimates of 2D and 3D attributes of seedlings and trees as an alternative to methods such as using TLS and traditional mensuration. As well as, TP method is a hardware low-demanding technique which does not require professional operator. Moreover, this workflow offers potential for application in urban greenings and nurseries inventory.

Technical and practical limitations and bottlenecks

One of the constraints discovered during the conducting of this study was the inability to estimate the average crown diameter attribute of trees within the sample plot due to the high density of trees and the overlap of tree crowns. Another constraint was the assessment of seedling trunk volume, which was less precise owing to the seedlings' tiny trunk diameter. Our review of the relevant literature showed that issues such as image quality, image overlap, and number of images, environmental conditions during photogrammetry, camera settings, as well as the applied hardware and software could affect the quality of output 3D models. The study of the effect of these factors on the quality of 3D output models could be the subject of our future research.

Conclusion

Our results showed that the 3D models that were generated using TP by a semi-professional handheld camera and the SfM-MVS method are capable of accurately estimating 2D attributes of seedlings and urban trees at three levels of seedlings, single trees and trees within a sample plot. According to obtained results, the diameter at the middle height of seedlings and DBH of trees were estimated with RMSE%< 2% at three levels. The height of single trees and trees within a sample plot were calculated with the highest and lowest accuracy, respectively, among the three levels. Nonetheless, seedling crown height was more precisely measured than the other two levels. The average diameter of the crown attribute at seedling and single tree levels were estimated with RMSE%= 6.51% and 9.34%, respectively. In this realm, the applied method estimated the stem volume of single trees and trees within the sample plot with practically appropriate accuracy, yet the 3D attributes of seedlings were less accurate (RMSE% more than 20%). This seems to be due to the small size of the seedlings and the difference in the estimated and measured values of the crown volume of the seedlings.

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Conflict of interest

The authors declare no conflict of interest.

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