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Additional Information

RESIDUAL BIOMASS CALCULATION FROM INDIVIDUAL TREE ARCHITECTURE USING TERRESTRIAL LASER SCANNER AND GROUND-LEVEL MEASUREMENTS

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Abstract

Large quantity of residual biomass with possible energy and industrial end can be obtained from management operations of urban forests. The profitability of exploiting this resource is conditioned by the amount of existing biomass within urban community ecosystems. Prior research pointed out that residual biomass from *Platanus hispanica* and other species trees can be calculated from dendrometric parameters. In this study, two approaches have been analyzed: First, applicability of TLS was tested for residual biomass calculation from crown volume. In addition, as traditional models to residual biomass prediction were developed from dendrometric parameters (tree height, crown diameter, and diameter at breast height). Next, a comparison between parameters obtained with both methodologies (standard methodologies *vs* TLS) was carried out. The results indicate a strong relationship (R^2=0.906) between crown diameters and between total tree heights (R^2=0.868). The crown volumes extracted from the TLS point cloud were calculated by 4 different methods: *convex hull*; *convex hull by slices* of 5 cm height in the XY plane; *triangulation* by XY flat sections, and *voxel* modelling. The highest accuracy was found when the voxel method was used for pruned biomass prediction (R^2=0.731). The results revealed the potential of TLS data to determine dendrometric parameters and biomass yielded from pruning of urban forests.

Key words: Urban forest, residual biomass, allometric relationships, volume equations, TLS, crown modelling, vegetation architecture.

INTRODUCTION

The management of urban forests requires pruning every year. This operation produces a significant amount of residual biomass, which has been usually underutilized. Most of urban residual biomass is not further processed and is accumulated in landfills. However, pruning can generate an important source of raw materials economically profitable in industrial processes such as bioenergy production. The profitability of exploiting these resources is conditioned by the amount of existing biomass within urban community ecosystems. Nevertheless, few studies have been conducted to quantify these materials. There is a lack of focus on individual tree biomass (McHale et al., 2009). Jenkins et al., (2004) observed that estimates of dry weight biomass of trees and particular tree parts are of great interest to managers, policymakers and researchers. Study by Pillsbury et al. (1998), noted that the urban forest inventories should describe composition, structure and volume of urban trees. To do this, data should be collected on tree parameters such as diameter at breast height, total tree height in addition to species location, health or damage rating.

Few studies have been conducted to quantify residual biomass. Sajdak and Velázquez-Martí (2012a) developed equations to calculate biomass from dendrometric parameters such us crown diameter or tree height. Despite the fact that accurate results can be obtained, using direct tree measurement is frequently time-consuming, expensive and forbidden in many environments. Plant structure investigation is now facing the possibility of replacing ground-level labour-intensive inventory practices with modern remote sensing systems (Lin et al., 2010). Many studies explore the applicability of Terrestrial Laser Scanning (TLS), Airborne Laser Scanning (ALS) and Vehicle-based

Laser Scanning (VLS) on biomass estimation and dimensions measurement at individual plant level. These technologies can create new observational tools for precise characterization of vegetation architecture within natural and plantation-like environments (Moorthy et al., 2011). The use of a TLS system in urban forests could allow three-dimensional modelling and geometrical characterization of trees, making it easier to develop management systems based on precise information.

TLS systems permit the characterization of the vertical distribution of vegetation structure (Radtke and Bolstad, 2001), that could replace manual field inventory practices. Information from these data can provide a better definition of plant architecture, as data from the whole plant. This information could be used to quantify the biomass available for energetic use what could be applied in urban trees (Fernández-Sarría et al., 2012). These systems have been used to estimate plant densities (Takeda et al., 2008; Hosoi and Omasa, 2006), ratio of wood in a plant (Clawges et al., 2007) and segmentation of tree stem diameters and branching structures (Henning and Radtke, 2006; Hopkinson et al, 2004; Thies et al., 2004). Moorthy et al., (2011), developed robust methodologies to characterize diagnostic architectural parameters such as crown width, crown height, crown volume and tree height in olive trees.

Several studies of TLS data aim to obtain geometric variables of tree crown height, width, surface area and volume (Tumbo et al., 2002, Lee and Ehsani, 2009, Moorthy et al., 2011). The crown volume is one of the most interesting parameter for plantation management. Classical dendrometry for crown volume calculation has been usually employed as variables in crop management: estimation of fruit yield (Lamien et al., 2007) and quantification of pruning residues (Velázquez et al., 2011a; Velázquez et al., 2011b). The main application of the comparison between classical and TLS methods for crown volume calculation is to analyze their relations in order to use the variable obtained from TLS data in crop management instead of the variable obtained from classical dendrometry. Many studies address the problem of crown volume calculation by several methods for different species of tree crops (Wei and Salyani, 2004) and vineyards (Palacin et al., 2008, Rosell et al., 2009). Other authors focus on the calculation of volume by the division of the point cloud in horizontal or vertical sections, estimating the solid volume between the different sections (Palacin et al., 2007) or deriving from these sections the ratio of the circumferences with the same surfaces (Moorthy et al., 2011).

Some studies used laser instruments mounted on mobile platforms known as vehicle-based laser scanning (VLS) in tree crops. While they are quite versatile, their accuracy is lower than the fixed TLS (Lee and Ehsani, 2009). Small variations in the distance between the sensor and the tree, as well as the speed of the platform produce errors above 9% in volume calculation. In contrast, Lin et al. (2010) argues that the TLS is less efficient comparing to VLS, due to laborious recollections especially for surveying multi-plots of trees. The authors suggest that biomass estimation at individual tree level will progress and become less money and time-consuming with VLS systems.

The main aim of this research has been the estimation of residual biomass in urban trees from crown volume derived from TLS data and from volume of revolution solids (hemisphere and paraboloid). These were obtained from dendrometric parameters (tree height, crown diameter, and diameter at breast height). A comparison of these parameters (standard methodologies *vs* TLS) was also carried out.

MATERIALS AND METHODS

Field study area

In this reserach, 30 specimen of *Platanus hispanica* (Münchh.) were scanned to calculate crown volume and to predict residual biomass coming from pruning. *Platanus hispanica* is extensively cultivated as an ornamental tree in parklands and roadsides in the temperate regions (Ballester-Olmos, 2009). Due to its high resistance to insect attacks, atmospheric pollution of large cities and root compaction, it became popular in urban zones (De La Torre, 2001). It is characterized by a rapid growth, great ease for transplantation and supports pruning operations well (López, 2010). Because of large areas where this species is cultivated in Mediterranean urban forests, the quantification and assessment of its residual becomes important. For this, it is key to establish the quantification of biomass received under particular pruning operations. The experiments were conducted on a municipal street of Alcudia, Spain (39^{o}28`50``N, 0$^{o}$21`59``W). The trees were selected to achieve the highest sample range possible. We chose a street of the city where the trees showed a suitable size distribution of the population of *Platanus hispanica*. We were forced to select only a street to improve the coordination tasks of pruning company and data collection. The area is defined with average annual temperature, rainfall and humidity of 17.8 ^{o}C, 454 mm and 65 %, respectively (www.aemet.es). Prior to data acquisition a pre-selection of sample trees was made. All individuals were pruned under uniform crown raising type after the measuring process had finished. This type of pruning consisted in removal of lower branches to provide crown elevation clearance for pedestrian and vehicle traffic as well as open views, visibility of lights and signs (Michau, 1987). For this study, 30 specimens of *Platanus hispanica* were chosen. The selected individuals were arranged on both sides of a road. The mean longitudinal space between sample trees was 20 m and the lateral spacing was approximately 12 m. This allowed the isolation of selected individuals, which was important for scanning, ground-level observations and further processing.

Field measurements

Ground-level studies were made to collect *in situ* measurements of some dimensional properties of sampled trees using traditional methods. Diameter at breast height (*dbh*) outside bark was measured with a traditional aluminium calliper in small trees or with a diameter tape in big trees at 1.3 m above ground level on the uphill side. Crown diameter (*dc*) was measured with a diameter tape and a mirror. Determination of crown diameter at field is complicated due to the irregularity of the crown's outline. For this the diameter was determined by averaging measurements of the long axis with a diameter taken at right angle. Total tree height (*h*) was determined with a Vertex IV hypsometer. It was measured from the base of the tree on the uphill side to the tip of the tallest live portion of the tree crown. Crown base height (*cbh*) was also determined with a Vertex IV hypsometer. The height was measured from the base of the tree on the uphill side to the base of the tree crown (*cbh*). As a reference for identifying the base of the canopy was taken the halfway between the first and one or more live branches (Dieguez et al., 2003; Husch et al., 2003; West, 2009).

Tripod-mounted TLS data collection

The instrument used in field trials was a Leica ScanStation2 laser scanner, based on time of flight technology with a dual-axis compensator. The TLS system used in this study emits a pulse of laser energy, scanning speed of 50,000 points per second, and a high resolution camera (http://hds.leica-geosystems.com). Its main technical characteristics are described in Table 1.

Table 1. Main characteristics of the equipment Leica ScanStation2 laser scanner

Instrument type	Pulsed, dual-axis compensated, very high speed laser scanner, with survey-grade accuracy, range and field of view	
Laser class	3R (IEC-60825-1) visible green	
Beam divergence	0,15 mrad	
Integrated color digital imaging	User defined pixel resolution; low, medium, high	
Scanning optics	Single mirror, panoramic, front and upper window design	
User interface	Notebook or tablet PC	
Accuracy of single measurement	Position (at 1-50 m range, 1σ): Distance (at 1-50 m range, 1σ): Angle (horizontal/vertical):	6 mm 4 mm 60 µrad / 60 µrad, 1σ
Model surface precision	2 mm, 1 σ	
Target acquisition	2 mm, 1 σ	
Dual-axis compensator	Selectable on/off; setting accuracy: 1.5’’	
Maximun range	300 m with 90% albedo, 134 m with 18% albedo	
Scan rate	Up to 50.000 points/second	
Scan resolution	Spot size: Point spacing:	≤ 6mm from 0-50m < 1 mm max. Fully selectable horizontal and vertical
Field of view (horizontal / vertical)	360º / 270º	

The Leica ScanStation2 laser scanner was mounted on a tripod and positioned so that there was a clear line between the scanner and the target sample tree. Specific locations were chosen in order to minimize the influence of obstructing elements. There have been a series of zig-zag shots to capture all sides of each sampled tree. The directions of scans were not predefined. The tree crowns are considered homogeneous in branches and leaves. In other words, they do not modify their characteristics according to the scan direction. Each position for scanning a tree was carried out the same day. All trees ware scanned in the end of the spring, when the crowns were with the maximum leaf area.

Prior to scan acquisition, various references or fixed points in the form of targets were placed both in the foreground and background surrounding the sample tree. These targets were used as ground control points to co-register the XYZ point clouds registered from two base stations. Return XYZ point clouds were acquired for all 30 trees and selected for detailed study. All data was obtained under calm conditions to limit movement errors caused by wind moving the leaves and branches of the sample tree crowns. A total of 13 base stations were established to measure the 30 sampled trees. Points were obtained every 5 mm, considering the mean distance from the laser to each sampled tree. Nevertheless, the scanning density was somewhat greater than 5 mm in the closest parts to the laser and lower in the furthest ones.

Each tree was measured using at least two stations. To merge the different clouds of points taken from the different stations, a minimum of four point targets or reference marks were measured. These points were used as link points. The absolute mean errors of the fitting operations were between 0.018 m and 0.003 m. After merging data, each tree was recorded in a single file to facilitate processing operations. Field data were processed with v.6 Cyclone Software (Leica Geosystems, [Heerbrugg] Switzerland). Since conventional 3D programs have limited tools, we developed several routines to obtain the crown diameter and crown volume with MATLAB® (further information related to the computation of crown volume by TLS can be found in Fernández-Sarría et al., (2012)).

Extraction of tree parameters from TLS point clouds

The primary tree structure parameters that were extracted from the TLS point clouds were the total tree height, crown base height, trunk height and crown diameter. Three files for each tree were generated: whole tree (*Total.xyz*), tree trunk (*Trunk.xyz*) and tree crown (*Crown.xyz*) respectively (Fig.1). The operator selected manually from the 3D point cloud which points belong to the crown and which points belong to the stem.

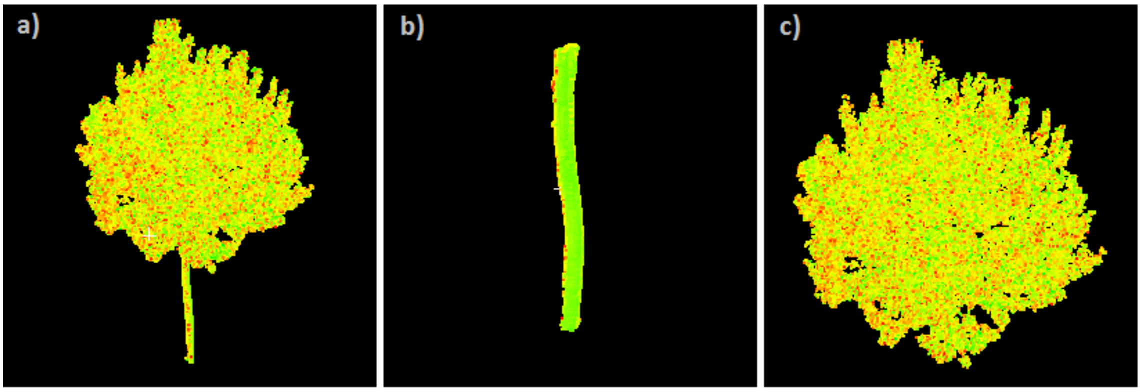

Figure 1. a) whole tree (Total. xyz), b) tree trunk (Trunk.xyz) and tree crown c) (Crown.xyz) point cloud files.

The total tree height was obtained using the *Total.xyz* file. It was estimated calculating the difference in laser pulse reflection from the top of the crown and the ground. The trunk height was calculated using the *Trunk.xyz* file. It was estimated using the difference in laser pulse reflection from the top of the trunk and the ground. When calculating the height of the crown the difference between total tree height and trunk height parameters was calculated. In order to obtain crown diameter, the average of the longest and the perpendicular diameters were determined. To analyze the crown diameter, the point cloud was projected over the ground. A reference point considered as the center of the trunk was selected. This was obtained using trunk specific point cloud (*Trunk.xyz*). All points located within 5 cm from the trunk top were selected to avoid an insufficient point number (Fig. 2). The average of X and Y coordinates was considered the reference point for diameter calculation. The reference point is considered accurate enough. There is no way of knowing the true central point without destructive sampling. The point density could affect this calculation but the differences among the density in the scanned sides was minimum, given that the scanning distances were quite similar from each viewpoint to each tree. In addition, each tree has been scanned from at least two viewpoints distributed to cover the whole tree even the trunk in a symmetrically way.

Figure 2. File A4T.xyz loaded in Cyclone for trunk center calculation.

Criteria of diameter selection

The *Total.xyz* point cloud was projected onto the XY plane (Fig. 3). Following formulas have been applied:

Increment of X, Y:

$$\Delta x = X_m - X_{pc}$$
$$\Delta y = Y_m - Y_{pc}$$

Distance from center point to the selected point:

$$\rho = \sqrt{\Delta x^2 + \Delta y^2}$$

Angle from the center point to the selected point:

$$\alpha = arctg \frac{\Delta x}{\Delta y}\left(\frac{180}{\pi}\right)$$

where: X_m and Y_m coordinates of the trunk's centre; X_{pc} and Y_{pc} coordinates of each point.

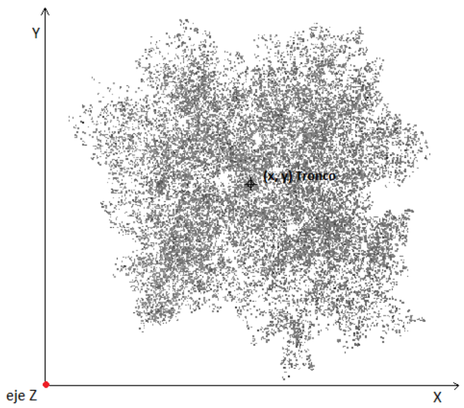

Figure 3. A [No.] C.xyz point cloud projected onto the XY plane.

To calculate this diameter, the following steps were performed:

Step 1. Calculation of the polar coordinates for each X, Y point (0^o and 360^o).

Step 2. Knowing the centre of the trunk, 72 circular sections were obtained using an interval of 5º.

Step 3. All radii within each section were calculated and the longest was selected (Fig. 4). If a section does not have any points the radius is calculated considering neighbour sections.

Step 4. The diameters were obtained by adding the radius of the first section (for the first diameter the radius of the section between 0° and 5º) and the radius of the section with an increment of 180º in respect to the angle of the first section (for the first diameter the radius of the section between 180° and 185º). The rest of diameters were determined in the same way obtaining a total of 36 diameters.

Step 5. The arithmetic mean of the longest (corresponding to the section with the most exterior point) and perpendicular diameters was considered the crown diameter for further calculations.

The tree dimensions extracted from TLS point clouds were compared with *in situ* measurements applied on the same individuals. This allowed comparing the accuracy of both methodologies by a variety of regression models. To determine models that provided the best fit, the coefficient of determination, standard deviation and mean absolute error were calculated.

Figure 4. Phases of diameter calculation.

Biomass estimation from crown volume

Once pruning operations ended, the residual biomass was formed in bundles and weighted by means of a dynamometer. Weight measurements were carried out in field conditions. Samples of wood were analysed to determine moisture content. The evaluation of drying process was done according to the norm UNE-EN 14774-2. The process was carried out in two types of conditions: open-air drying with average temperature 21.32 ºC and relative humidity 42.41 %, stove drying with temperature 105 ºC. Several branches of each sample-tree were defoliated to determine the percentage of foliage and wood mass. Apparent volume of a tree crown was related with the biomass yielded from pruning. For this, equations for apparent volume calculation for particular solids of revolution were applied. It is assumed, that growth models of tree crowns resemble the form of hemispheric, parabolic and conical growth (Table 2) (Dieguez et al., 2003).

Table 2. Growth models

Geometric solid	Equation for Volume
Cone	$v_c = \frac{\pi \cdot dc^2 \cdot ch}{12}$
Paraboloid	$v_c = \frac{\pi \cdot dc^2 \cdot ch}{8}$
Hemisphere	$v_c = \frac{\pi \cdot dc^3}{12}$

v_c: apparent crown volume (m^3); *dc*: crown diameter (m); *ch*: crown height (m).

The crown volume has been also extracted from the TLS point clouds by means of four processing algorithms implemented in MATLAB, described in Fernández-Sarría et al, (2012):

- *Global convex hull* (Method 1): Application of a convex hull (convhulln function) of the point cloud in each crown.

- *Convex hull by slices* (Method 2): Application of a convex hull (convhulln function) of the points belonging to slices of 5cm of height in each crown.

- *Volume calculation by sections* (Method 3): Division of the crown's point cloud into sections of 10 cm of height and calculation of the area of each section by

Delaunay triangulation. The total volume was obtained adding the surface of each section multiplied by 10 cm.

- *Rasterization in voxels* (Method 4): Transformation of the point cloud into small units of volume using a grid in three-dimensional space (voxel). For the examined models the coefficient of determination (R^2), standard deviation (sd) and mean absolute error (MAE) were calculated.

It is important to point out that the distance from the scanner to the tree as well as its angle affects the registered number of points in the scanning process. Nevertheless, the methods used to calculate volume and dendrometric data use only the external points which define the canopy (except for voxel). Therefore the different data density produces minimum variations in the volume and parameters calculated taking into account the dimensions of the trees in the study area. In the case of voxel modeling, the voxel size (20x20x20 cm^3) used in our study is large enough to not be affected by the small variation of data density. The voxel is counted in the calculated volume either it is occupied by only a point or a lot of them. Besides they are appropriated to detect the internal structure of the tree and it is large enough compared to the accuracy of the measurements performed by the TLS.

RESULTS AND DISCUSSION

Tree height (*h*), distance from soil to the crown (*cbh*), crown height (*ch*) and crown diameter (*dc*) were the four parameters obtained from TLS and from manual *in situ* measurements (Table 3).

Table 3. Tree parameters extracted from field data and TLS point clouds (in m).

Tree number	h	hTLS	cbh	cbh TLS	ch	ch TLS	dc	dc TLS
1	10.200	9.776	3.100	3.382	7.100	6.394	6.450	6.383
2	9.200	9.126	2.500	3.165	6.700	5.961	5.000	4.952
3	12.500	12.234	4.200	4.255	8.300	7.979	8.850	10.688
4	10.500	10.095	3.400	3.386	7.100	6.709	6.550	6.481
5	12.700	11.754	3.900	3.711	8.800	8.043	8.250	10.724
6	12.300	12.878	3.700	3.898	8.600	8.980	8.100	8.054
7	11.200	11.469	3.400	4.176	7.800	7.293	8.300	8.730
8	12.200	11.660	4.100	4.283	8.100	7.377	7.400	7.774
9	11.800	11.105	4.300	4.308	7.500	6.797	8.100	8.728
10	12.000	12.085	3.900	3.564	8.100	8.521	8.650	9.238
11	6.400	9.108	2.300	2.915	4.100	6.193	5.600	5.921
12	8.200	11.362	3.200	4.037	5.000	7.325	8.300	8.006
13	11.000	10.614	3.700	3.597	7.300	7.017	7.850	8.166
14	11.500	11.244	4.600	4.314	6.900	6.930	8.310	8.660
15	9.400	9.692	3.900	3.307	5.500	6.385	5.620	5.944
16	9.200	9.414	4.100	3.575	5.100	5.839	5.410	5.762
17	10.300	10.318	4.200	3.707	6.100	6.611	6.300	7.105
18	10.400	10.772	3.900	3.936	6.500	6.836	6.750	6.972
19	12.400	12.197	3.800	3.904	8.600	8.293	9.500	9.950
20	8.500	8.948	2.200	2.249	6.300	6.699	4.100	4.279
21	13.300	12.581	2.600	4.094	10.700	8.487	10.860	12.124
22	9.200	9.287	3.100	3.722	6.100	5.565	5.600	5.105
23	12.600	12.722	3.900	3.820	8.700	8.902	9.740	10.504
24	13.200	12.706	3.600	4.431	9.600	8.275	10.350	10.776
25	9.900	12.348	3.400	3.781	6.500	8.567	9.420	10.081
26	12.000	11.617	3.700	4.133	8.300	7.484	7.890	8.477
27	11.800	10.222	4.600	3.983	7.200	6.239	9.370	8.228
28	13.000	12.893	4.000	3.991	9.000	8.902	10.970	11.193
29	11.800	12.397	4.200	4.741	7.600	7.656	9.350	9.287
30	11.300	11.554	3.800	3.949	7.500	7.605	10.350	11.584
Maximum	13.300	12.892	4.600	4.740	10.700	8.979	10.970	12.124
Minimum	6.400	8.948	2.200	2.248	4.100	5.565	4.100	4.279
Mean	11.000	11.139	3.643	3.810	7.356	7.328	7.909	8.329
Standard deviation	1.678	1.272	0.626	0.495	1.442	0.990	1.835	2.120

h: total tree height (m); *cbh*: distance from soil to the crown (m); *dc*: crown diameter (m); *ch*: crown height (m); *TLS*: Terrestrial Laser Scanning.

To compare results obtained with both methodologies an analysis of variance was performed (Fig. 5).

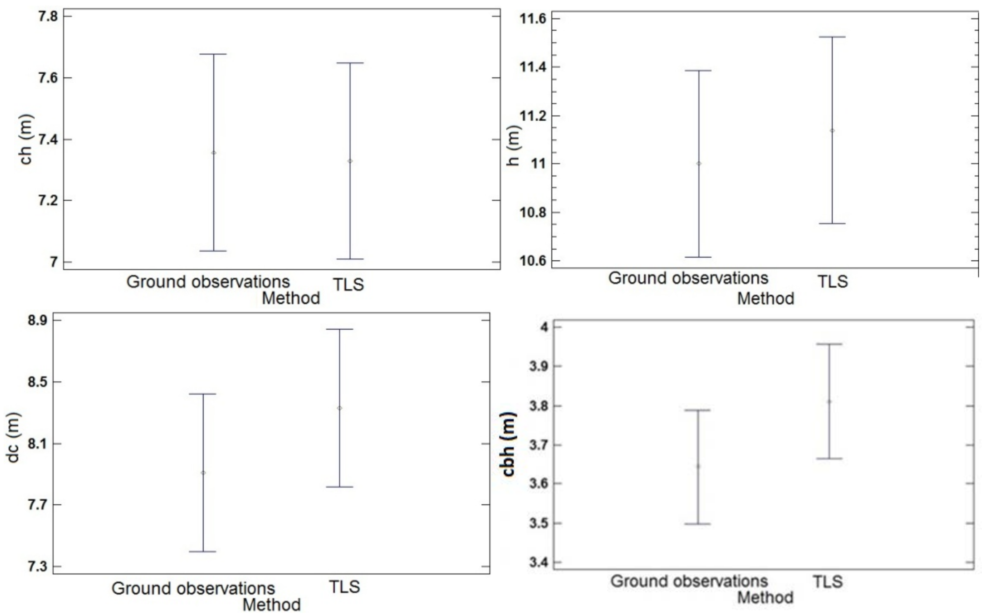

Figure 5. Intervals of statistical comparison of the dendrometric measurements carried out manually and by means of TLS at 99% level of confidence: *ch*: crown height (m); *h*: total tree height (m); *dc*: crown diameter (m); *cbh*: distance from soil to the crown (m).

The results indicate that there are no significant differences (P-values<0.05) for the analyzed parameters obtained using the two different methods. The values of total tree heights obtained by two techniques are very similar if we consider the differences between their means (0.14 m). The crown diameters calculated manually in field trials are lower than those extracted from TLS point clouds. This may be explained by the fact that the selection of both largest and perpendicular diameters may be less accurate from field measurements. One reason of this underestimation may be attributed to the existence of obstructing elements (neighbour trees). In many cases the border between branches of neighbour tree crowns is hard to define from ground level. Furthermore, it should be noted that when crown diameter is measured, the line should pass through the centre point of the trunk, what is impossible to obtain in field measurements (without destructive sampling). These results could suggest that the accuracy of these measurements could be less exact than of the parameters derived by TLS. They are obtained applying an algorithm with several steps that allow selecting in an unbiased way, the longest diameter of 36 values computed by tree. Moreover, according to the specifications of the technical report of the TLS, points were registered every 5 mm. An inter-comparison of structural parameters has been made for data obtained with both methodologies (Fig. 6).

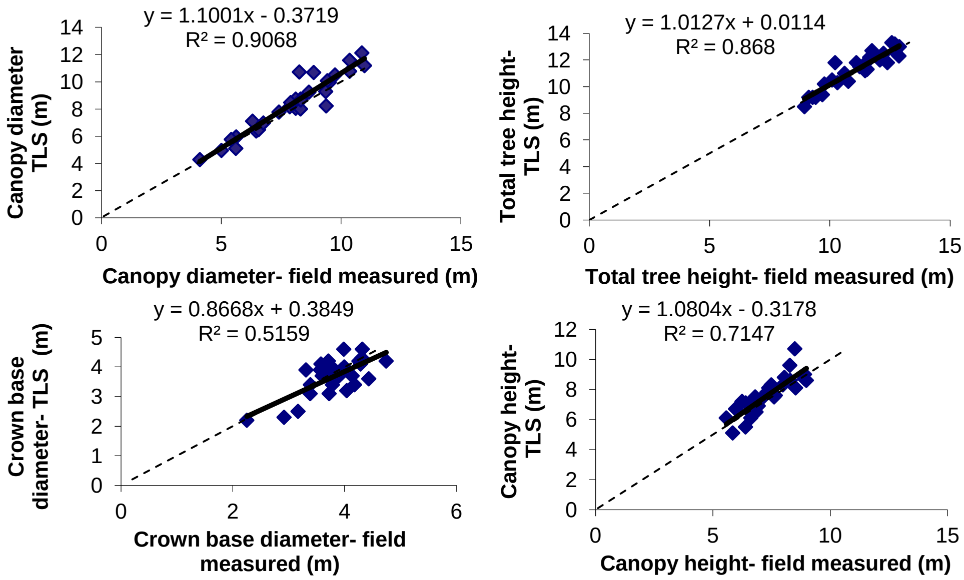

Figure 6. Inter-comparison of parameters obtained from TLS point clouds and ground observations: canopy diameter; total tree height; distance from soil to the crown; canopy height. (p-value<0.001 in all equations).

The results indicate a strong relationship (R^2 = 0.906) between crown diameters and a good relationship between total tree heights (R^2 = 0.868). In contrast, the lowest correlation was found for the parameter distance from soil to the crown base height (R^2

= 0.516). This may be explained by the criteria followed for the selection of the canopy base. In the case of manual measurement, the reference for identifying the base of the tree crown was taken the halfway between the first and one or more live branches. When using the TLS point cloud, the distances were extracted from the files containing 3D scans of tree trunks and total tree heights.

Biomass estimation by TLS and ground observations

It could be noted that wood formed 43.34 % of total weight of all pruned material before drying. The rest (56.66 %) of weight was formed by leaves and fruit. Wood moisture content was 40.16 % in wet basis. The mean and standard deviation of pruned biomass for all sample trees were 23.98 kg and 15.16 kg, respectively. Pruned biomass was correlated with the four methods for deriving the crown volume by TLS data (Fig. 7).

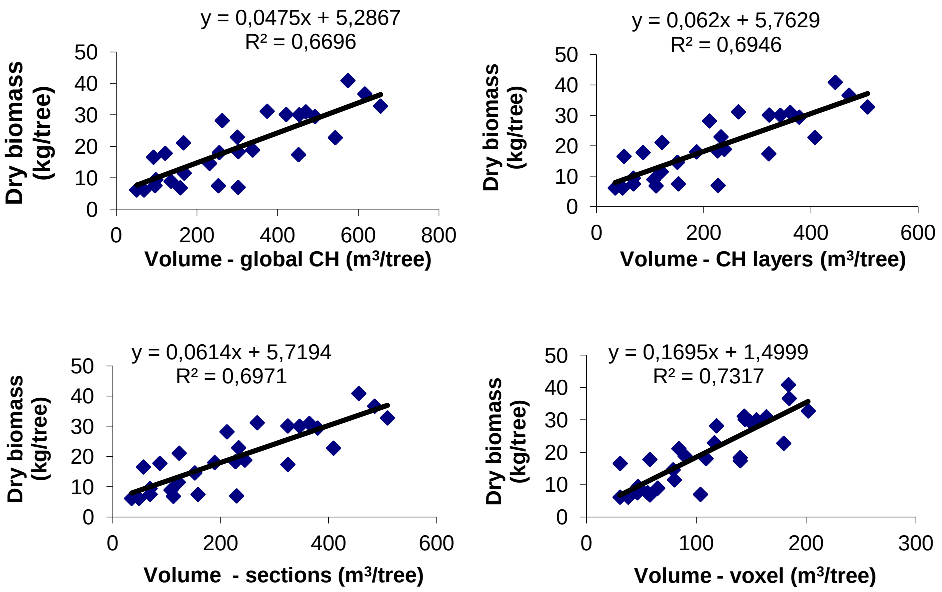

Figure 7. From left to right and up to down: Relationship between 4 methods of TLS volume calculation and yielded biomass from 28 sample trees: global CH; CH slices; sections, voxels. (p-value<0.001 in all equations).

As can be observed in Figure 7 the range of volume values using the voxel method were significantly different from the other methods. The volume ranges for the three other methods were approximately 0-600 m^3 whereas the range for the voxel method was 0-200 m^3. This can be explained because the methods global CH, CH slices, and Sections calculate the volume included inside the canopy (volume of the solid surface defined by the boundary of the canopy). In contrast, the voxel method provides lower crown volume values because some internal materials are not registered in the scanning process.. In addition, this method discards holes in the canopy of the crown what produces a better performance of the crown structure . The volume calculated with this method provides equations with better coefficient of determination to predict residual biomass.

The results are similar for all analysed models. The best coefficient of determination (R^2=0.731) is observed between biomass and crown volume obtained using the voxel method. This is explained by the accuary of voxel method and best adjustment to crown architecture. It is necessary to emphasize that all methods used for estimating residual biomass from crow volume are very similar according to the coefficients of determination (0.67 – 0.73). Although the voxel modeling gave the best performance to estimate residual biomass, another factors such as processing time could be taken into account to select the optimal method. Biomass obtained from pruning was also related with geometrical volumes (Fig. 8).

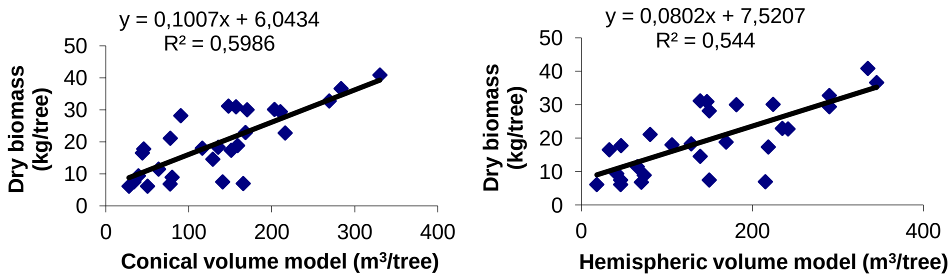

Figure 8. Relationship between 2 methods of volume calculation (cone, hemisphere) and yielded biomass from 28 sample trees. (p-value<0.001 in all equations).

The conical and parabolic volume models are proportional and indicate a coefficient of R^2=0.598. The R^2 values of these models are lower than those obtained using TLS data what could indicate a higher precision of TLS techniques over ground-level measurements. The significant values of coefficients obtained with both methodologies suggest the existence of a relationship between examined parameters and the possibility for predicting biomass.

CONCLUSIONS

This study demonstrated the capability of TLS system to predict residual biomass from pruning of *Platanus hispanica*. It has demonstrated that the equations derived from crown volume calculated with TLS data explain more variability of pruned biomass than those obtained from volume of revolution solids (hemisphere and paraboloid). The inter-comparison of pruned biomass with volumes extracted from point clouds revealed that the highest accuracy was obtained for the voxel method. This shows a better performance of the crown structure due to the fact that this method discards holes in the canopy of the crown.

The results of this research could be applied to quantify the potential biomass in urban forests what has been little studied so far, being able to apply to other species. In addition, this study has allowed obtaining other tree parameters such as tree height, crown diameter, and canopy height which are less accurate and more difficult to obtain in urban environments by standard methodologies.

We must highlight that the crown diameter can be extracted with more accuracy considering the scan resolution of a TLS system and applying a suitable methodology that could be used for other species. Crown diameter is usually considered a relevant predictive variable in the estimation of the main dendrometric parameters. Crown diameter obtained by TLS is strongly related with data obtained from ground observations. These methodologies can be more efficient than time-consuming ground methods that show the disadvantage of being affected by observer errors.

This research can contribute to improve the knowledge of species within urban community ecosystems allowing an improvement of the quantification and management of residual biomass.

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