Different Methodologies for Calculating Crown Volumes of *Platanus hispanica* Trees using Terrestrial Laser Scanner and a Comparison with Classical Dendrometric Measurements

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Abstract

Terrestrial laser scanners (TLS) are used in forestry and fruit culture applications to perform a three-dimensional geometrical characterization of trees and so make it easier to develop management systems based on that information. In addition, this data can improve the accuracy of dendrometric variable estimations, such as crown volume, obtained by standard methods. The main objective of this paper is to compare classical methods for crown volume estimation with the volumes obtained from the processing of point clouds obtained using a terrestrial laser scanner (TLS) on urban *Platanus hispanica* trees. This will allow faster quantification of residual biomass from pruning and therefore an improved management in future. The methods applied using TLS data were also evaluated in terms of processing speed. A set of 30 specimens were selected and their main dendrometric parameters (such as diameter breast height, crown diameter, total height, and distance from the crown base to the soil) were manually measured using classical methods. From these dendrometric parameters, the apparent crown volumes were calculated using three geometric models: cone, hemisphere, and paraboloid. Simultaneously, these trees were scanned with a Leica Scanstation2. A laser point cloud was registered for each tree and processed to obtain the crown volumes.

Four processing methods were analyzed: a) *Convex hull* (an irregular polyhedral surface formed by triangles that surround the crown) applied to the whole point cloud that forms the crown; b) *Convex hull using slices* of 10 cm in height from the top to the base of the crown; c) *XY triangulation in horizontal sections*; and d) *Voxel discretization.*

All the obtained volumes (derived from classical methods and TLS) were assessed and compared. The regression equations that compare the volumes obtained by dendrometry and those derived from TLS data showed coefficients of determination (R^2) greater than 0.78. The highest R^2 (0.89) was obtained in the comparison between the volume calculated using a paraboloid and flat sections, which was also the fastest method. These results show the potential of TLS for predicting the crown volumes of urban trees, such as *Platanus hispanica,* to help improve their management, especially the quantification of residual biomass.

Keywords: Laser scanner, canopy volume, convex hull, voxel.

1. Introduction

LIDAR technology (light detection and ranging) is an active remote sensing system that emits energy that returns to the sensor after contacting an object. Information produced can be recorded on a massive scale for three-dimensional surfaces, either of the Earth if installed in an aircraft (aerial LIDAR); or for objects scanned from land (terrestrial LIDAR). LIDAR systems are based on either phase differences or on measurements of time between the emission and reflection of an energy pulse after reaching the targets (return trip). Aerial LIDAR records the return signal of an emitted pulse at different echoes while the use of a GPS and an inertial system allow calculating the coordinates of the point where the reflection takes place. This data can be processed to derive digital terrain models (DTM), digital surface models (DSM), and canopy height models of vegetation (CHM). These models are widely used to define applications in several fields such as: hydraulic modeling (Cobby et al., 2001); building representation (Hermosilla et al., 2011); changes in beach sand volumes (Shrestha et al., 2005); and especially in forestry applications (Lefsky et al., 1999; Næsset, 2002; Maltamo et al., 2006; Popescu, 2007; Estornell et al., 2011).

Terrestrial LIDAR systems (terrestrial laser scanner or TLS) is based on the same principles as airborne LIDAR although operational use differs. Both provide X, Y, and Z point cloud coordinates of the scanned object in a specific or local reference system. This data can then be used to generate three-dimensional models. This technology is increasingly used in several fields such as: manufacturing (Cheng et al., 1995), construction (Arayici, 2007), civil engineering (Riveiro et al., 2011; Slattery et al., 2012), cultural heritage (Guidi et al., 2003), criminal investigation (Cavagnini et al., 2007; Sansoni et al., 2009), forestry and agricultural applications (Moorthy et al.m, 2011). The data registered from a TLS can be used to define tree structure in great detail because the trees can be scanned on all sides. Airborne LIDAR provides less detail in the lower and lateral parts but airborne and terrestrial data can be combined to improve detail. In forest studies, TLS was also used for: comparing tree modeling data with the data obtained by airborne LIDAR or classical instrumentation (Kato et al., 2008); analyzing structure (Gorte and Pfeifer, 2004; Parker et al., 2004) in large and homogeneous forest environments (Lovell et al., 2003); and calculating resistance to water flow in riparian areas (Antonarakis et al., 2009).

Numerous studies relate dendrometric variables obtained using traditional methods with important parameters for forest and fruit culture management such as: the dose of pesticide to be applied (Palacin et al., 2007); growth rates and productivity (Lee and Ehsani, 2009); estimating the biomass of each tree as indicator of health status (Lin et al., 2010); and the quantification of wood waste generated in pruning (Velázquez-Martí et al., 2011a; Velázquez-Martí et al., 2011b). Consequently, a better knowledge of the relationship between the variables derived from TLS data and dendrometric characteristics of vegetation can be useful for the above applications..

Previous studies of TLS data were focused on obtaining geometric variables of the tree crown, such as 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 variables for the management of plantations. Traditionally, this term has been defined as the apparent geometric volume that includes all the branches and leaves even the holes among them (Hamilton, 1969; Dieguez et al., 2003). Dendrometry has been usually based on the proportionality principle of the structure sizes, which are a characteristic of species (Velazquez et al., 2010). The relationship between crown volume and biomass was pointed out in Forrester at al., 2012 or Velazquez et al., 2012 in citrus trees. Several studies addressed the problem of its calculation for different species of tree crops (Wei and Salyani, 2004) and vineyards (Palacin et al., 2008; Polo et al., 2009). From these crown volume values, leaf indices such as LAI (leaf area index) and LAD (leaf area density) can be estimated (Moorthy et al., 2011; Rosell et al., 2009).

Some authors use a three-dimensional matrix where the smallest element of information is the voxel (Hosoi and Omasa, 2006; Stoker, 2009). Models based on this concept, such as the *voxel-based canopy profiling* (VCP) model (Hosoi and Omasa, 2006), enable to estimate LAD and LAI profiles of small trees. The *voxel-based light interception model* (VLIM) (Van der Zande et al., 2010), enable estimating the percentage of incident sunlight that passes through the crown canopy and help determine the LAI on trees at different stages of leaf growth. With the *K-dimensional tree algorithm* (Park et al., 2010) clouds of points can be discretized in voxels and the data is resampled at different resolutions. This method offers several advantages (Stoker, 2009) such as: the coordinates of each voxel can be used for processing; points measured from successive shots are considered as a single voxel without oversampling; three-dimensional models can be analyzed as digital images; the exterior and interior of trees can be modeled if the laser signal penetrates sufficiently into the tree crown from different stations. Other authors have focused on dividing the point cloud into horizontal or vertical sections and then estimating the volume of the solids between the different sections (Palacin et al., 2007). Moorthy et al. (2011) estimated the volume deriving from these sections the radii of the circles with the same surface. These studies are particularly noteworthy as they also used the *convex hull algorithm* applied to flat sections of the point cloud. The convex hull of a set of points on a plane (or in a space) is the smallest of the areas or volumes that contain the set of points (Graham, 1972). This algorithm compared with the Savitzky-Golay filter and values derived from direct field data is recognized as one of the most accurate approaches in the study of the plant growth and productivity (Lee and Ehsani, 2009).

Many of these studies have used two-dimensional laser equipment mounted on mobile platforms to scan tree crops. However, the accuracy of this equipment is not comparable with fixed instruments. Errors greater than 9% in the volume calculation may be caused by small variations in the distance between the sensor, the tree, and platform speed; as well as slight changes in the tree shape (Lee and Ehsani, 2009).

In this paper, we have worked with a highly accurate device to model the crown of ornamental *Platanus hispanica* trees. This species is very vigorous and needs annual or biannual pruning; thereby generating a large amount of organic waste that needs to be managed. A prediction of residual biomass from pruning can be made from the whole canopy volume (Sajdak et al., 2011; Velázquez-Martí et al., 2011c) and this operation can be automated by applying TLS techniques. Our research is initially focused on comparing volumes obtained from different methodologies: classical dendrometry and three-dimensional models generated from TLS data. Four different algorithms to calculate crown volumes were applied to the TLS data. These were compared with three geometric shapes for measuring diameters and heights: cone, paraboloid, and hemisphere. The accuracy of the obtained volumes from TLS data and the number of operations is also evaluated. This provides valuable information for the automation of surveys and management systems based on biomass (Velázquez-Martí and Annevelink, 2009). These techniques could be extended to fruit tree species to predict production and the amount of nutrients and pesticides required for the crown volumes.

2. Material and methods

The instrument used in this work was a Leica ScanStation2 laser scanner with a dual-axis compensator and a high resolution camera (http://hds.leica-geosystems.com). The scanning speed was high (50,000 points per second). The main technical characteristics are described in Table 1. Various accessories were also included with the device (such as a laptop, tripod, batteries, and aiming marks) as shown in Figure 1.

Table 1: Main characteristics of the 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’’	
Maximum 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	

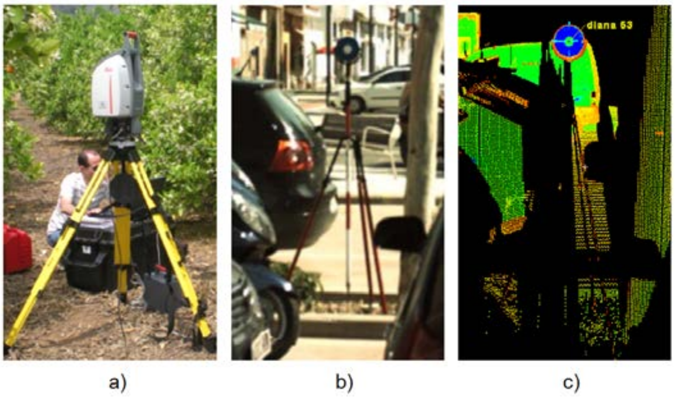
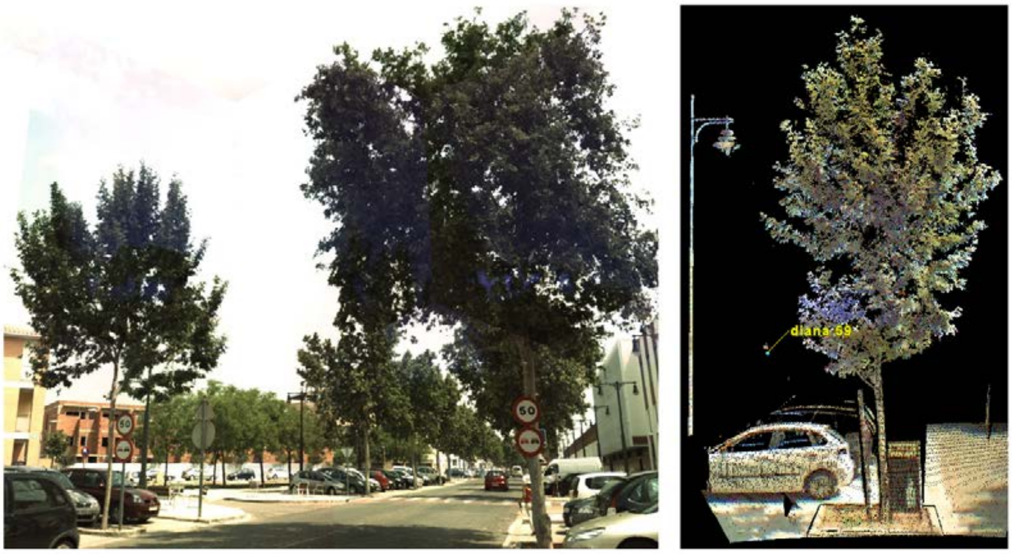


Figure 1: (a) Leica ScanStation2 with necessary accessories; (b) aiming mark mounted on tripod, and (c) scanned target.

2.1. Field data collection and processing

For this work 30 urban trees of *Platanus hispanica* were selected in L'Alcudia, a city in the Spanish province of Valencia. This species is common in Mediterranean cities, grows quickly, and generates significant volumes of residual biomass after pruning (López González, 2010). The sampled trees were on both sides of a street (Figure 2a). The width between the tree lines was 12 m. The mean distance between trees of the same line was 20 m. This enabled a differentiation between the point clouds of the various trees, which was important for scanning and further processing tasks. To register every side of each tree, most were scanned from at least two points by stations on both sides of the street alternately. Nevertheless, some trees were only scanned from one point due to the size of tree, proximity to buildings, obstructions, etc.

The average age of the studied trees was between 10-12 years, their heights were between 6 m and 17 m, and the crown diameters measured between 4.1 m and 13.3 m.



a) b)

Figure 2: a) Picture of scanned trees in the urban area. b) Obtained scan data, where elements other than the tree must be filtered.

Thirteen stations were used to measure the 30 trees. The device was leveled at each station, and after starting the computer, several photographs of the area were taken to define the scanning windows. The basic settings for the TLS scanning, such as ambient temperature, atmospheric pressure, and scan resolution (points every 5 mm) were then selected. For each station, objects or surfaces around the trees were also scanned (street furniture, walls, parked or moving vehicles, and people (see Figure 2b) and these were later eliminated.

To merge the different clouds of points taken from the different stations, a minimum of four point targets or references were measured. These points were used as link points. The absolute mean errors of the fitting operations were between 0.018 and 0.003 m. After merging data, each tree was recorded in a single file to facilitate processing operations. Scanning data was processed using Cyclone v.6 software provided by Leica. This software was used to remove points not belonging to the trees.

2.2. Methods for determining crown volume using TLS data

Different approaches to calculate the crown volumes were used. Four processing algorithms were implemented using MATLAB (MathWorks, Inc.) and the accuracy and number of operations (processing speed) were analyzed. (Figure 3):

- *Global convex hull*: Application of a convex hull of the point cloud in each crown.
- *Convex hull by slices*: Application of a convex hull of the points belonging to slices 5 cm in height in each crown.
- *Volume calculation by sections*: Isolation of the cloud crown points for every 10 cm of height and the calculation of the area of each section using Delaunay triangulation. The total volume was obtained by adding the surface of each section multiplied by 10 cm.
- *Rasterization in voxels*: Transformation of the point cloud into small units of volume using a grid in three dimensional space (voxel).

Figure 3 shows the geometrical shapes for the crown volume calculation for each method.

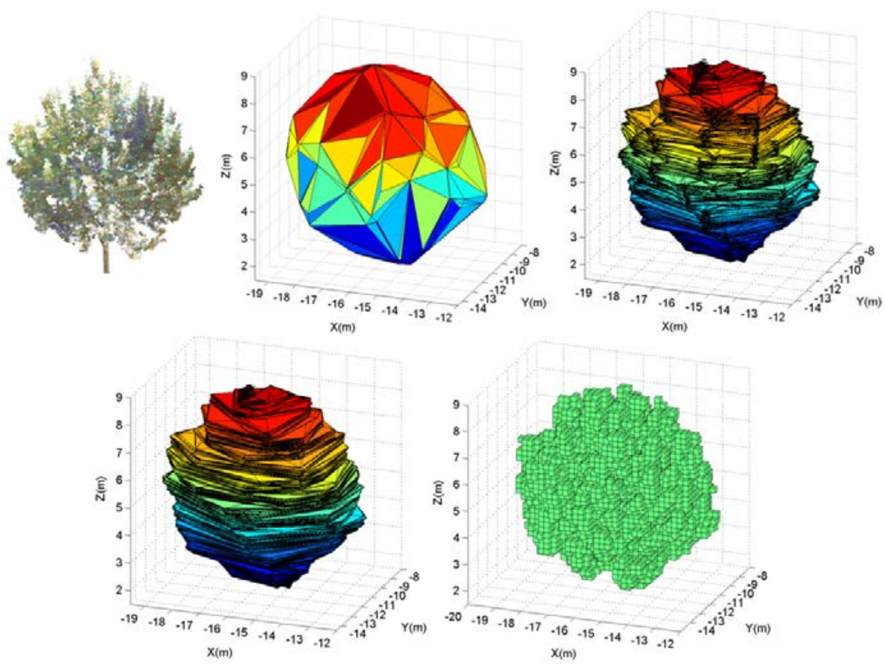


Figure 3: Representation of the four algorithms used to derive crown volume from a TLS data. From left to right and top to bottom: picture of the scanned crown; global convex hull; convex hull by slices; planar triangulation by sections; and voxel.

Method 1: *Global convex hull (Global CH).* In three-dimensional space, the convex hull is the boundary of a closed convex surface generated applying Delaunay triangulations with the outer points. This surface is composited by triangles formed from the exterior points of the cloud. The convex hull can be determined by various algorithms, such as: incremental, gift wrap, divide and conquer and quickhull (Barber et al., 1996). The convhulln function based on the quickhull algorithm was implemented in Matlab. This algorithm removes the points that are not within the boundary of the closed convex hull (i.e. interior points). To do this, the following steps were carried out:

Step 1: Six exterior points of the cloud were selected (maximum and minimum X, Y, Z) to generate an irregular octahedron. Not all points within this polyhedron belong to the boundary. The points outside this octahedron were divided into eight separate regions for each side (Figure 4a).

Step 2: The point with the longest distance to the plane formed by an octahedron side was selected in each region. In this way, eight new points were selected to generate a new figure of 14 vertices (six initial points from step 1 and another eight from step 2). Twenty-four new triangles were formed between the vertices (Figure 4b). The points within the new figure were also removed.

Step 3: The previous steps were repeated by selecting new points whose distance to the new triangle sides were maximums and so generated new polyhedrons. The algorithm finishes when there are no points outside of the geometrical figure created in each step. This irregular polyhedron with *n* sides is the convex hull and its volume can be calculated.

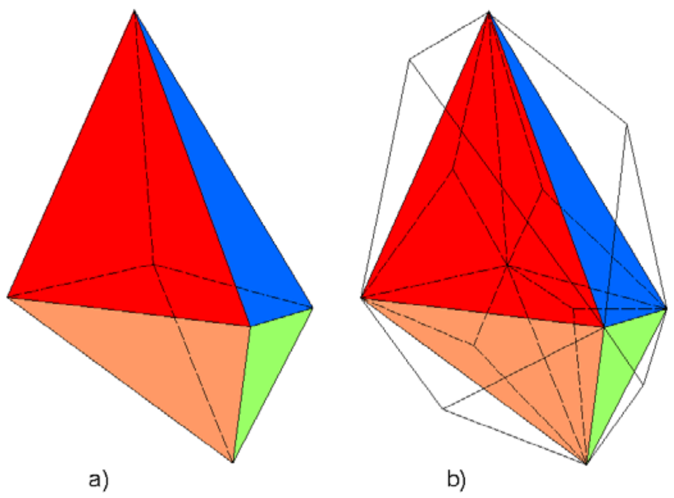


Figure 4: Initial steps for convex hull formation.

This algorithm shows a computational complexity that can be measured by O(n logn) (asymptotic notation that expresses the computation requirement when the crown point number, n, is changed). The main drawback of this method is that it does not take into account the empty spaces corresponding to the many gaps between the outer branches, where no points are registered.

Method 2: *Convex hull by slices (CH slices).* This method is based on the same algorithm as Method 1 applied to slices of 5 cm in height (Figure 3). The Delaunay triangulation was carried out in the XY plane, and so obtaining better approximation in the Z axis.

From the minimum height of the crown, all points located between 0 and 5 cm in height were selected and the convex hull method was applied (Method 1). This method was then applied for the points located between 5 and 10 cm. The process was repeated for every following slice of 5 cm in height. The final volume was obtained adding the single volumes of all the slices. More operations take place than in Method 1 given that the convex hull function is applied to each slice.

Method 3: *Volume calculation by sections (Sections).* The crown tree was divided into slices of 10 cm in height. Firstly, in this algorithm a horizontal plane was defined by selecting the lowest point of the crown. From this value, all points within a slice of ±2 cm in height were selected and considered to be in the same plane by ignoring their *Z* coordinate. A triangulation was then applied to the points considered in the same horizontal plane and the area of the section was calculated. This step was repeated for every 10 cm of crown height. From consecutive sections the volume of each slice was calculated by Equation 1:

$$V = \frac{S1 + S2}{2} \cdot h \tag{1}$$

where *S1* and *S2* are the areas of the consecutive sections, and *h* is the separation between sections (10 cm). The whole volume is the sum of all the single volumes between two sections.

Method 4: *Rasterization in voxels (Voxel).* A volumetric pixel (voxel) is the minimum discrete volume that can be processed in a tridimensional object (Hosoi and Omasa, 2006). This method is based on organizing the point cloud in a tridimensional regular grid where each cell with at least one point inside is a voxel (Figure 4). The volume of each voxel is summed to calculate total volume and the shape of the crown can be obtained. To calculate the volume using the voxel concept the following steps were performed:

Step 1. The minimum and maximum *X, Y, Z* coordinates of the point cloud were selected from the initial three-dimensional model. A tridimensional grid was built with a cell size of 20 cm.

Step 2. The X_{min}, X_{max} coordinates of first voxel were labeled. All points with X coordinates between those *X-limits* then created a set associated to the first sections (S_1) in the YZ plane.

Step 3. The Y_{min}, Y_{max} coordinates of the first voxel were defined, and from the points selected in step 2, a new set of points with coordinates *Y* between those *Y-limits* was selected to create the (C_1) column in the *Z* axis.

Step 4. The Z_{min}, Z_{max} coordinates of the first voxel were also calculated. From points selected in step 3, only those whose *Z* coordinates were between those limit values were included in the first V_1 voxel. The coordinates of the V_1 voxel and the presence-absence of points within it were stored in a matrix. The same steps were followed for the remaining voxels $(V_2$ to $V_n)$ of the $C_1 - S_1$. This algorithm was then applied from column C_2 to C_n and then from S_2 to S_n.

The final result is a matrix of coordinates for each voxel indicating the internal presence or absence of points. The total volume is obtained by multiplying the number of voxels with points inside by the volume of a voxel (8000 cm^3). The structure of the tree crown can be depicted from the location of each voxel (Figure 3).

These four methods enable the calculation of crown volume and other dendrometric variables such as tree height, trunk and crown height, and crown diameter. These variables allow us to establish relationships with classical manual measurements as well as residual biomass from pruning.

2.3. Volume calculation by classic dendrometry

Every tree was characterized by its crown diameter and crown height. Crown diameter (dc) was measured with a diameter tape with precision 0.001m and a mirror. The diameter was determined by averaging measurements of the long axis with a diameter taken at right angle (Dieguez Aranda et al., 2003, Husch et al., 2003, West, 2009). The crown diameter was reported in m. Crown height (hc) was determined with a Vertex IV hypsometer with precision 0.01 m. The Vertex IV hypsometer uses ultrasonic pulses together with a transponder fixed to a tree. The crown height was measured from the base of the crown (first bifurcation) on the uphill side to the tip of the tallest live portion of the tree crown (Husch et al., 2003, West, 2009). The total height was reported in m.

The apparent volumes of the tree crowns were estimated from crown diameter and height by applying three geometric shapes: cone, paraboloid and hemisphere:

Cone: $$V = \frac{\pi \cdot dc^2 \cdot hc}{12} \quad (2)$$

Paraboloid: $$V = \frac{\pi \cdot dc^2 \cdot hc}{8} \quad (3)$$

Hemisphere: $$V = \frac{\pi \cdot dc^3}{12} \quad (4)$$

where V is the apparent crown volume, dc is the crown diameter, and hc is the crown height. Equations (2) and (3) are proportional at a factor of 2/3. Between equations (3) and (4) there is a relationship that is dependent on the diameter and crown height (Equation 5). Therefore, this factor is not constant but will show a populational variation that defines a mean and standard deviation for *Platanus hispanica* trees.

$$K = \frac{2}{3} \cdot \frac{dc}{hc} \quad (5)$$

3. Results and Discussion

Table 2 contains the values of the crown volumes of 30 specimens of *Platanus hispanica* obtained from TLS data by applying the previously mentioned methods (Global CH, CH slices, Sections, and Voxel) and from field measurements obtained by applying solids of revolution (palaboloid, hemisphere, and cone). The greatest values of volume calculated from TLS data were obtained using the Global CH method, followed by Sections and the CH Slices methods, which are very similar. The lowest volumes were obtained using the Voxel method. This result can be explained by the fact that some holes are detected within the crown due to the occultation of the external leaves – branches or the absence of them (Figure 5). The volumes calculated using solids of revolution from classical dendrometry were lower than those obtained from TLS data.

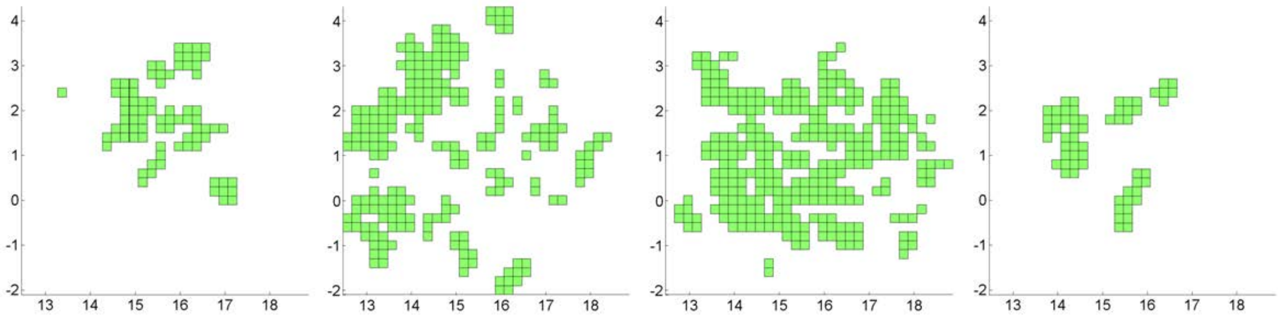


Figure 5: Position of the voxels in four horizontal sections at 3, 5, 7 and 9m height for Tree 1.

There is a large dispersion in the population (standard deviations) because the sampled trees had different degrees of development (growth). The young trees showed a vertical development and the mature trees (most of the sampled trees) reveal a horizontal expansion whose geometric shape is close to a paraboloid. The values of skewness and kurtosis were close to 0 and this indicates a good approximation to the normal distribution.

Table 2: Volumes obtained (m^3) for the seven methods of calculation and basic statistics.

Tree	Global CH	CH slices	Sections	Voxel	Paraboloid	Hemisphere	Cone
1	158.507	110.795	112.467	57.792	115.936	70.215	77.291
2	92.067	51.062	56.821	30.728	65.744	32.708	43.829
3	453.550	342.757	346.226	154.800	255.155	181.375	170.103
4	135.506	106.565	108.002	64.928	119.559	73.531	79.706
5	469.964	361.212	364.273	163.832	235.088	146.930	156.725
6	373.886	264.515	267.615	143.576	221.467	139.060	147.644
7	253.084	152.600	158.025	55.704	210.907	149.618	140.604
8	255.396	186.479	188.882	108.856	174.096	106.034	116.064
9	231.140	150.603	152.181	78.904	193.139	139.060	128.760
10	338.176	238.303	244.790	89.720	237.879	169.354	158.586
11	95.792	68.700	69.369	46.368	50.466	45.953	33.644
12	262.582	210.508	211.695	118.432	135.197	149.618	90.131
13	266.960	191.687	194.920	95.400	176.564	126.578	117.709
14	299.902	231.968	233.209	116.512	252.199	235.142	168.133
15	121.156	86.598	87.463	57.712	68.183	46.447	45.455
16	97.862	68.201	69.204	46.912	58.587	41.432	39.058
17	168.221	120.377	121.516	79.984	95.028	65.429	63.352
18	166.568	121.871	123.087	84.112	116.241	80.475	77.494
19	421.478	321.895	324.458	144.512	304.639	224.346	203.093
20	50.378	34.498	34.953	30.576	41.567	18.034	27.711
21	574.407	445.218	455.843	183.928	495.317	335.149	330.211
22	68.461	48.369	48.855	38.000	75.084	45.953	50.056
23	543.039	407.184	408.998	179.600	323.949	241.783	215.966
24	655.265	505.587	508.816	201.904	403.638	290.115	269.092
25	451.879	321.273	324.448	139.944	226.389	218.726	150.926
26	302.348	225.924	227.402	139.944	202.802	128.523	135.201
27	302.074	226.575	229.661	103.800	248.114	215.262	165.409
28	616.338	470.859	485.143	184.624	425.104	345.437	283.403
29	397.968	306.732	308.606	150.536	260.781	213.886	173.854
30	492.739	377.859	379.631	149.048	315.342	290.115	210.228
Maximum	655.265	505.587	508.816	201.904	495.317	345.437	330.211
Minimum	50.378	34.498	34.953	30.576	41.567	18.034	27.711
Mean	303.890	225.226	228.219	108.023	203.472	152.210	135.648
Stand. Dev.	173.358	135.433	137.037	51.177	115.942	92.837	77.295
Skewness	0.367	0.434	0.450	0.106	0.638	0.452	0.638
Kurtosis	-0.862	-0.813	-0.781	-1.190	0.124	-0.678	0.124

As can be observed in the Table 3, the comparison between each two methods from linear regression models show high determination coefficients. The analysis of the methods applied to the TLS data shows R^2 greater than 0.92. When these methods were compared to those derived from classical dendrometry, the R^2 values were slightly lower (0.86 - 0.89). The lowest values were found when the volumes obtained using voxels were compared to those calculated using a paraboloid (R^2=0.78) and a hemisphere (R^2=0.75).

Table 3: Equations relating crown volumes calculated by different methods and R^2.

Equation / R^2	**Paraboloid**	**Hemisphere**	**Global CH**	**CH slices**	**Sections**	**Voxel**
Paraboloid		y=1.205x+20.054	y=0.631x+11.586	y=0.806x+21.827	y=0.799x+20.967	y=2.005x-13.157
Hemisphere	0.931		y=0.496x+1.426	y=0.636x+9.041	y=0.630x+8.527	y=1.569x-17.316
Global CH	0.891	0.858		y=1.276x+16.508	y=1.261x+16.028	y=3.251x-47.284
CH slices	0.887	0.860	0.993		y=0.988x-0.281	y=2.565x-51.855
Sections	0.893	0.864	0.994	0.999		y=2.589x-51.460
Voxel	0.784	0.748	0.921	0.940	0.935	

3.1. Comparison of the classic volumes by dendrometry

Figure 6 compares the volumes obtained using the paraboloid and hemisphere models. The dashed line represents the bisector line where both volumes are equals. It can be observed that the crown volumes obtained from the paraboloid model are greater than those obtained from the hemisphere model (points appearing above the dashed line). However, some exceptions were found that could be explained by considering factors such as pruning or distance to buildings that may affect the growth and shape of the trees. It can also be observed that the points are distributed uniformly along the trend line, which shows the absence of anomalous points. In addition, there was a proportionality among the volumes calculated using both paraboloid and hemispheric geometric shapes according to Equation (5). The results obtained from the dendrometrical measurements in a field of 30 specimens show that the average of the proportionality factor was 0.72 (Table 4) with a standard deviation of 0.13.

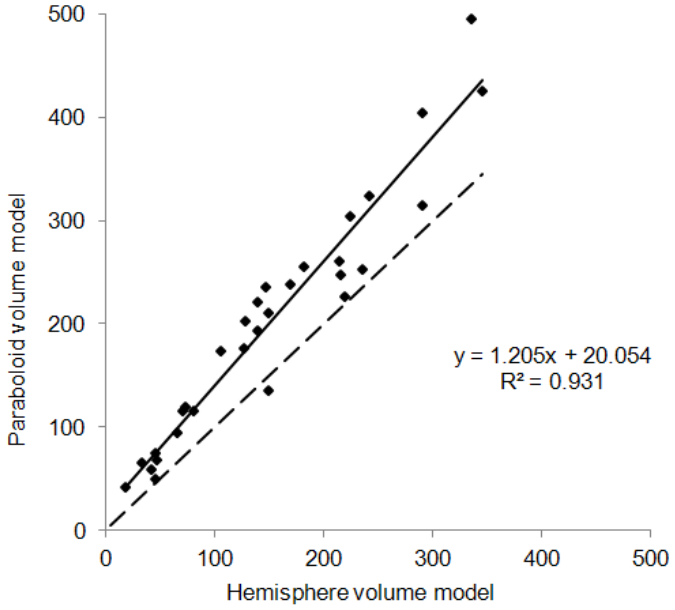


Figure 6: Paraboloid versus hemisphere volume for the crown (m^3).

Table 4: Statistical values of proportionality factor between the paraboloid crown model and hemisphere crown model.

3.2. Comparison of the volumes obtained from terrestrial laser scanner

The Global CH method provided the highest values for volumes. This is consistent with the nature of the approach, which creates a solid surrounded by triangles whose vertices are the most exterior points of the cloud data registered by the TLS. This volume includes all internal holes in the crown and external spaces between branches, thereby generating an overestimation of the apparent volume.

The three-dimensional modeling by voxels gave the lowest values for volumes, approximately one third lower than the volumes obtained by the previous method. This can be explained by the fact that rasterization is made on existing points within a tridimensional cell (voxel). When there are no points within those cells, the voxel is not considered for the calculation of total volume. Therefore, this method is the best performer given the actual shape of the crown with its branches and leaves. Nevertheless, this method may have the disadvantage of not including the volume of internal materials due to the occultation generated by the external leaves or branches of the tree. For these reasons, while these volume values are lower than the actual actual volumes, which are understood as the solid parts of the plant or crown (only branches and leaves). The voxel method provides lower values of crown volume than the actual volumes because some internal materials are not registered in the scanning process. In addition, the crown voxel method is also lower than the apparent volumes calculated by the methods *global CH*, *CH slices*, and *Sections*, which are the volume included inside the canopy (volume of the solid surface defined by the boundary of the canopy) . All of them can still be used to calculate dendrometric variables, such as crown diameter and height, and can be related with residual biomass.

The comparison between volumes generated by the Global CH and Voxel methods shows the highest standard deviation in differences (125.7 m^3). However, the equation that relates both volumes has a $R^2 = 0.92$.

The CH slices and Sections volumes show very similar results with lower volume values than those obtained by Global CH. The first two methods divide the total crown volume into horizontal planes, which gives a better approximation to the actual shape of the crown at each height. For this reason, the void space counted by these methods outside crown canopy is lower than that counted by Global CH. As can be observed in Table 3, the comparison between volumes generated using the CH slices and Sections methods shows an almost perfect equivalence between them, with an R^2 of 0.99. Similar results were obtained for the comparison between volumes obtained by the Global CH and CH slices methods ($R^2 = 0.99$). Good results were also obtained among volumes obtained using the CH slices and Voxel methods ($R^2 = 0.94$).

3.3. Comparisons between dendrometric volumes and volumes calculated using laser scanner

A comparative analysis was performed for finding relationships between the volumes obtained applying classical dendrometry and TLS data processing (Table 3). Values of R^2 were between 0.74 and 0.89. All volumes obtained from TLS data were higher than those obtained from the classical models – except for the volumes obtained from voxel quantification.

Figure 7 shows the scatter plots relating the results of the paraboloid volume model with the TLS data based models. It is observed that the volumes of smaller trees were usually located near the diagonal. Greater differences were found for mature trees and this could be explained by the greater irregularities in their crowns. The relationship between the paraboloid and volume calculation by sections gave the highest coefficient of determination (R^2). It is important to note that the findings for this method are also very close to the CH slices method. The volumes obtained by quantification of voxels gave the lowest values and the equations had the smallest R^2. These good correlations between geometric volumes and TLS volumes allows their conversion to profit all management studies developed up to now from dendrometric measures.

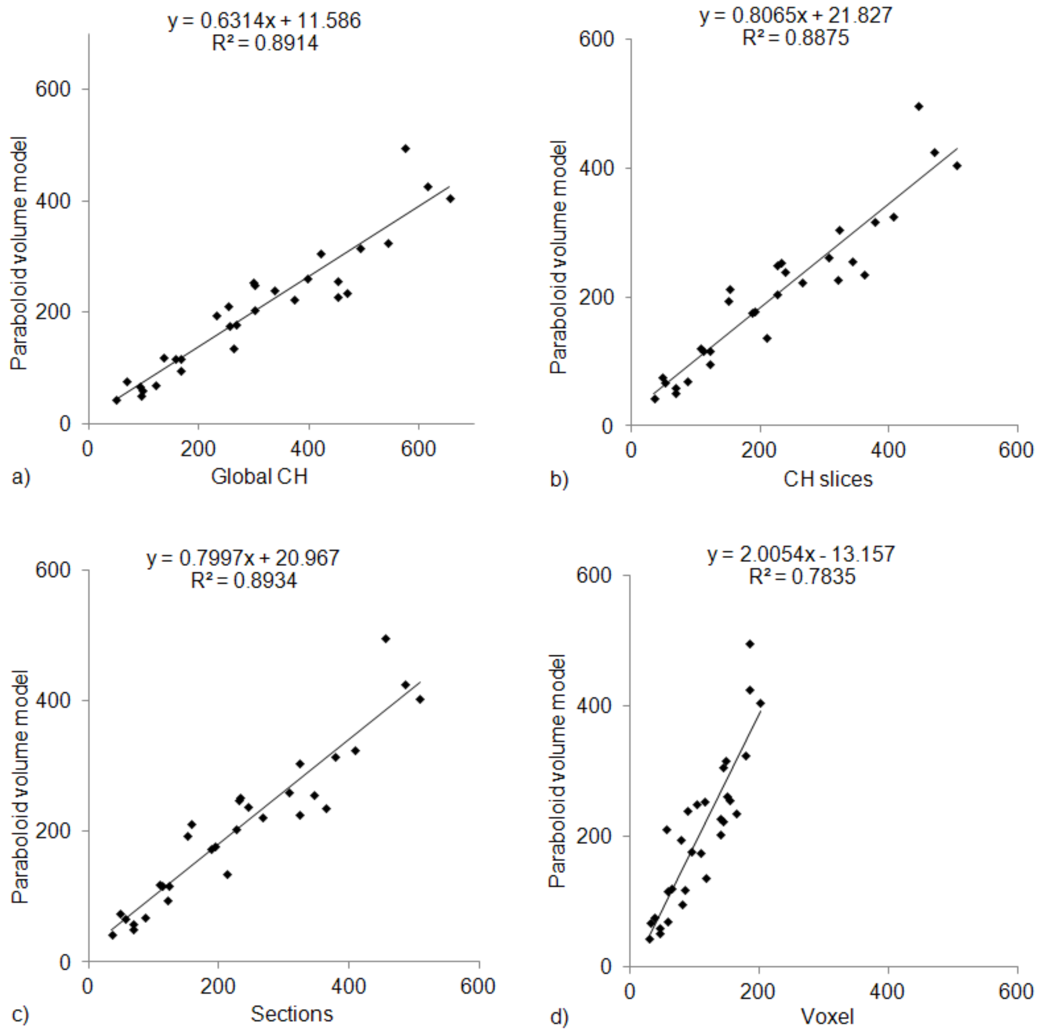


Figure 7: Relationships between volumes of the paraboloid (m^3) and volumes obtained from TLS (m^3).

An important variable when evaluating each method is the number of operations required and processing time. Figure 8 shows a comparative analysis of this parameter for the four methods used to process the cloud points obtained from the laser scanner. As can be observed, the processing time increases with the size and shape of the crown. Few differences were found for smaller trees (minor number of points). However, there were very significant differences for larger crowns.

The Voxel method generated the highest variation of processing time, being almost three times longer than the time required for the computation of volume using the Sections method in large trees. This increase was not linear. The Global CH and the CH slices were the fastest methods, and showed the lowest increase in processing time for larger crown sizes. These variations were linear with a low gradient.

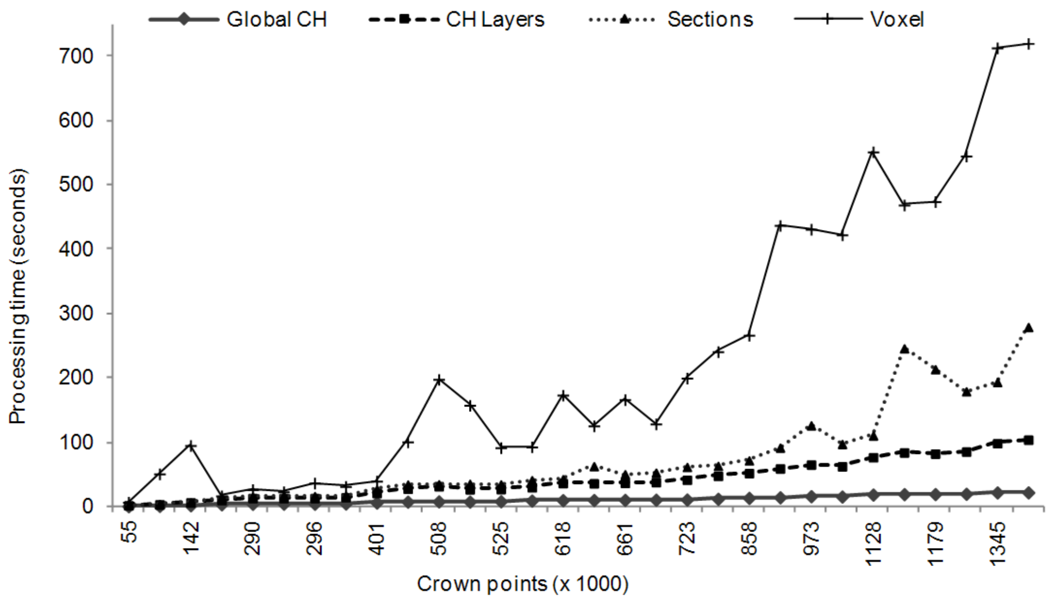


Figure 8: Processing time for the four methods applied to laser data for crown volume calculation.

4. Conclusions

Four methods developed for processing TLS data were compared with three traditional geometrical models used for calculating the apparent volume of 30 *Platanus hispanica* tree crowns. These dendrometric measurements are frequently applied for tree species in natural environments with wild conditions of growth and development. In this work, these measurements were applied to urban trees where special growing conditions exist: planting, watering, pruning, and barriers to growth such as buildings.

It has been demonstrated that the volumes of smaller trees calculated using laser scanners are usually more proportional to classical paraboloid volumes than the volumes calculated for larger trees (due to their greater irregularities). The processing method based on calculation by sections and the paraboloid method showed the maximum correlation to calculate crown volume values. Considering the parameters of this geometric shape, this method could also be suitable for defining other parameters such as crown diameter and height. It is important to note that the findings of this method are also very close to those obtained using the CH slices method.

The method based on volume calculation by sections and convex hull by slices minimizes the overestimation generated by the global convex hull method. The voxel method provided the smallest values for volumes and was considered the best approximation to the real shape of the crown. This fact is caused by the partial detection of the inner structures and the complete detection in the canopy. For this reason this method could be considered appropiate for estimating the biomass of trees, although, this does not prevent the occultation of points inside the crown by external leaves and branches completely. Voxel rasterization cannot be used to calculate actual volume for this limitation. Another disadvantage is the higher computational time used to perform the calculations. In contrast, Global CH and CH slices are the fastest methods and only show a small increase in processing time.

All the studied methods applied to TLS data show high levels of correlation with the volumes obtained using classical geometrical models. These models are related with variables used for plantation management, such as: volume of residual biomass from pruning or use of fitosanitary products. The methods developed in this study from TLS data may offer an important advantage for the management of the studied trees. They allow to obtain a 3D model of the tree crown considering all their irregularities. According to the good correlations obtained with the standard dendrometric volume (paraboloid) and the low number of operations required, Global convex hull is recommended as an alternative to classical methods for estimating crown volume.

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References

Antonarakis, A.S., Richards, K.S., Brasington, J., Bithell, M., 2009. Leafless roughness of complex tree morphology using terrestrial lidar. Water Resour. Res. 45, W10401.

Arayici, Y. 2007. An approach for real world data modelling with the 3D terrestrial laser scanner for built environment. Automation in construction 16 (6): 816-829

Barber, C.B., Dobkin, D.P., Huhdanpaa, H.T., 1996. The quickhull algorithm for convex hulls. ACM Trans. Math. Softw. 22(4), 469-483.

Cavagnini, G.; Scalvenzi, M.; Trebeschi, M.; Sansoni, G. Reverse engineering from 3D optical acquisition: application to Crime Scene Investigation. In Virtual and Rapid Manufacturing - Advanced Research in Virtual and Rapid Prototyping; Bártolo, P.J. et al. Eds.; Taylor & Francis Group: London, UK, 2007; pp. 195-201

Cheng, W.L.; Menq, C.H. Integrated laser/CMM system for the dimensional Inspection of objects made on soft material. Int. J. Adv. Manuf. Tech. 1995, 10, 36-45.

Cobby, D.M., Mason, D.C., Davenport, I.J., 2001. Image processing of airborne scanning laser altimetry data for improved river flood modelling. ISPRS J. of Photogramm. Remote Sens. 56(2), 121-138.

Dieguez Aranda U., Barrio Anta M., Castedo Dorado F., Ruiz Gonzalez A. D., Alvarez Taboada M. F., Alvarez Gonzalez J. G., Rojo Alboreca A. 2003. Dendrometria. Ediciones Mundi-Prensa.

Estornell, J., Ruiz, L.A., Velázquez-Martí, B., 2011. Estimation of shrub biomass by airborne LiDAR data in small forest stands. For. Ecol. Manag. 262, 1697–1703.

Forrester D I, Collopy J, Beadle C L, Baker T G. 2012 Interactive effects of simultaneously applied thinning, pruning and fertiliser application treatments on growth, biomass production and crown architecture in a young Eucalyptus nitens plantation. Forest ecology and management 267:104-116.

Gorte, B., Pfeifer, N., 2004. 3D image processing to reconstruct trees from laser scans. In Proceedings of the 10th annual conference of the Advanced School for Computing and Imaging (ASCI), Ouddorp, the Netherlands.

Graham, R.L., 1972. An efficient algorithm for determining the convex hull of a finite planar set. Inf. Process. Lett. 1, 132-133.

Guidi G, Beraldin JA, Atzeni C. 2004. High-accuracy 3-D modeling of cultural heritage: The digitizing of Donatello. IEEE Transactions on Image Processing 13(3): 370-378.

Hamilton J. 1969. The Dependence of Volume Increment of Individual Trees on Dominance, Crown Dimensions, and Competition *Forestry* 42(2): 133-144 G

Hermosilla, T., Ruiz, L.A., Recio, J.A., Estornell J., 2011. Evaluation of automatic building detection approaches combining high resolution images and LiDAR data. Remote Sens. 3(6), 1188-1210.

Hosoi, F., Omasa, K., 2006. Voxel-based 3-D modeling of individual trees for estimating leaf area density using high-resolution portable scanning lidar. IEEE Trans. Geosci. Remote Sens. 44, 3610-3618.

Husch B., Beers T.W., Kershaw J. A. Jr. 2003. Forest Mensuration. John Wiley & Sons, INC.

Kato, A., Moskal, L.M., Stuetzle, W., Swanson, M.E., Schiess, P., Calhoun, D., 2008. New high-resolution field surveying methods for validation of crown attributes from 3D scanning laser data. In Proceedings of ASPRS 2008 Annual Conference, Portland, Oregon.

Lee, K.H., Ehsani, R., 2009. A laser scanner based measurement system for quantification of citrus tree geometric characteristics. Appl. Eng. Agric. 25, 777-788.

Lefsky, M., Cohen, W., Acker, S., Parker, G., Spies, T., Harding, D., 1999. Lidar remote sensing of the canopy structure and biophysical properties of Douglas-fir western hemlock forests. Remote Sens. Environ. 70, 339-361.

Lin, Y., Jaakkola, A., Hyyppa, J., Kaartinen, H., 2010. From TLS to VLS: Biomass Estimation at Individual Tree Level. Remote Sens. 2, 1864-1879.

López González, G.A., 2010. Guía de los árboles y arbustos de la Península Ibérica y Baleares. Ediciones Mundi-Prensa, Madrid.

Lovell, J.L., Jupp, D.L.B., Culvenor, D.S., Coops, N.C., 2003. Using airborne and ground-based ranging lidar to measure canopy structure in Australian forests. Can. J. Remote Sens. 29, 607-622.

Maltamo, M., Eerikainen, K., Packalen, P., Hyyppa, J., 2006. Estimation of stem volume using laser scanning-based canopy height metrics. Forestry. 79, 217–229.

Moorthy, I., Miller, J.R., Jimenez Berni, J.A., Zarco-Tejada, P., Hu, B., Chen, J., 2011. Field characterization of olive (*Olea europaea L.*) tree crown architecture using terrestrial laser scanning data. Agric. For. Meteorol. 151, 204-214.

Næsset, E., 2002. Predicting forest stand characteristics with airborne scanning laser using a practical two-stage procedure and field data. Remote Sens. Environ. 80, 88–99.

Palacin, J., Palleja, T., Tresanchez, M., Sanz, R., Llorens, J., Ribes-Dasi, M., Masip, J., Arno, J., Escola, A., Rosell, J.R., 2007. Real-time tree-foliage surface estimation using a ground laser scanner. IEEE Trans. Instrum. Meas. 56, 1377-1383.

Palacin, J., Palleja, T., Tresanchez, M., Teixido, M., Sanz, R., Llorens, J., Arno, J., Rosell, J.R., 2008. Difficulties on Tree Volume Measurement from a Ground Laser Scanner. In Proceedings of 2008 IEEE Instrumentation and Measurement Technology Conference, Vols 1-5, pp. 1997-2002.

Park, H.J., Lim, S., Trinder, J.C., Turner, R., 2010. Voxel-based volume modelling of individual trees using terrestrial laser scanners. In Proceedings of 15th Australasian Remote Sensing & Photogrammetry Conf, Alice Springs, Australia, pp. 1125-1133.

Parker, G.G., Harding, D.J. and Berger M.L., 2004. A portable LIDAR system for rapid determination of forest canopy structure. J. Appl. Ecol. 41, 755-767.

Polo, J.R.R., Sanz, R., Llorens, J., Arno, J., Escola, A., Ribes-Dasi, P., Masip, J., Camp, F., Gracia, F., Solanelles, F., Palleja, T., Pal, L., Planas, S., Gil, E., Palacin, J., 2009. A tractor-mounted scanning LIDAR for the non-destructive measurement of vegetative volume and surface area of tree-row plantations: A comparison with conventional destructive measurements. Biosyst. Eng. 102, 128-134.

Popescu, SC., 2007. Estimating biomass of individual pine trees using airborne lidar. Biomass & Bioenergy. 31(9), 646-655.

Riveiro B, Morer P, Arias P, de Arteaga I. 2011. Terrestrial laser scanning and limit analysis of masonry arch bridges. Construction & building materials 25(4): 1726-1735.

Rosell, J.R., Llorens, J., Sanz, R., Arno, J., Ribes-Dasi, M., Masip, J., Escola, A., Camp, F., Solanelles, F., Gracia, F., Gil, E., Val, L., Planas, S., Palacin, J., 2009. Obtaining the three-dimensional structure of tree orchards from remote 2D terrestrial LIDAR scanning. Agric. For. Meteorol. 149, 1505-1515.

Sajdak, M., Velázquez-Martí, B., Fernández-Sarría, A., Estornell, J., 2011. Estimation of pruning biomass through the adaptation of classic dendrometry on Mediterranean urban forests: case study of *Platanus hispanica*. In Proceedings of VI Congreso Ibérico de Agrolngeniería, Évora, Portugal.

Sansoni G, Trebeschi M, Docchio F. 2009. State-of-The-Art and Applications of 3D Imaging Sensors in Industry, Cultural Heritage, Medicine, and Criminal Investigation. Sensors 9(1): 568-601.

Slattery K T, Slattery D K, Peterson J P. Road Construction Earthwork Volume Calculation Using Three-Dimensional Laser Scanning. Journal of surveying engineering 138(2): 96-99.

Shrestha, R., Carter, W., Slatton, K., Luzum, B., Sartori, M., 2005. Airborne Laser Swath Mapping: Quantifying changes in sandy beaches over time scales of weeks to years. ISPRS J. Photogramm. Remote Sens. 59(4), 222-232.

Stoker, J., 2009. Volumetric Visualization of Multiple-Return Lidar Data: using Voxels. Photogramm. Eng. Remote Sens. 75, 109-112.

Tumbo, S.D., Salyani, M., Whitney, J.D., Wheaton, T.A., Miller, W.M., 2002. Investigation of laser and ultrasonic ranging sensors for measurements of citrus canopy volume. Appl. Eng. Agric. 18, 367-372.

Van der Zande, D., Stuckens, J., Verstraeten, W.W., Muys, B., Coppin, P., 2010. Assessment of Light Environment Variability in Broadleaved Forest Canopies Using Terrestrial Laser Scanning. Remote Sens. 2, 1564-1574.

Velázquez-Martí B., Annevelink E., 2009. GIS application to define biomass collection points as sources for linear programming of delivery networks. Transactions of ASABE. 52(4), 1069-1078.

Velázquez-Martí, B., Fernández-González, E., López-Cortes, I., Salazar-Hernández, D.M., 2011a. Quantification of the residual biomass obtained from pruning of vineyards in Mediterranean area. Biomass & Bioenergy. 35(3), 3453-3464.

Velázquez-Martí, B., Fernández-González, E., López-Cortes, I., Salazar-Hernández, D.M., 2011b. Quantification of the residual biomass obtained from pruning of trees in Mediterranean olive groves. Biomass & Bioenergy. 35(2), 3208-3217.

Velázquez-Martí, B., Estornell, J., López Cortés, I., Martí-Gavilá, J., 2011c. Calculation of biomass volume of the citrus trees in base on adapted dendrometry focused on management of the plantations and energy or industrial utilization of its residual. In Proceedings of XXXIV CIOSTA CIGR V Conference 2011, Vienna, Austria.

Velazquez Marti B, Estornell J, Lopez Cortes I, Marti Gavila J. 2012. Calculation of biomass volume of citrus trees from an adapted dendrometry. Biosystems engineering 112(4): 285-292.

Wei, J., Salyani, M., 2004. Development of a laser scanner for measuring tree canopy characteristics: Phase 1. Prototype development. Transactions of the ASAE, 47, pp. 2101-2107.

West P.W. 2009. Tree and Forest Measurement. Springer-Verlag Berlin Heidelberg.