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Estimation of structural attributes of walnut trees based on terrestrial laser scanning

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Abstract: *Juglans regia* L. (walnut) is a tree of significant economic importance, usually cultivated for its seed used in the food market, and for its wood used in the furniture industry. The aim of this work was to develop regression models to predict crown parameters for walnut trees using a terrestrial laser scanner. A set of 30 trees was selected and the total height, crown height and crown diameter were measured in the field. The trees were also measured by a laser scanner and algorithms were applied to compute the crown volume, crown diameter, total and crown height. Linear regression models were calculated to estimate walnut tree parameters from TLS data. Good results were obtained with values of R^2 between 0.90 and 0.98. In addition, to analyze whether coarser point cloud densities might affect the results, the point clouds for all trees were subsampled using different point densities: points every 0.005 m, 0.01 m, 0.05 m, 0.1 m, 0.25 m, 0.5 m, 1 m, and 2 m. New regression models were calculated to estimate field parameters. For total height and crown volume good estimations were obtained from TLS parameters derived for all subsampled point cloud (0.005 m – 2 m).

Keywords: dendrometry, walnut tree, laser scanner, convex hull, precision agriculture.

Estimación de parámetros de estructura de nogales utilizando láser escáner terrestre

Resumen: *Juglans regia* L. (nogal) es un árbol de importancia económica por el fruto que proporciona y por su madera utilizada en la industria del mueble. El objetivo de este trabajo fue calcular modelos de regresión para estimar los parámetros altura total, altura, diámetro y volumen de copa de nogales utilizando datos registrados mediante un escáner láser terrestre. Un conjunto de 30 árboles fueron escaneados y se aplicaron algoritmos para calcular los parámetros anteriores, que también se midieron en campo utilizando técnicas tradicionales. Se obtuvieron buenos resultados, con valores de R^2 entre 0,90 y 0,98 para todos los parámetros. Además, para analizar la relación entre la densidad de puntos registrada y la precisión en la estimación de los parámetros de los nogales, las nubes de puntos de todos los árboles fueron sub-muestreadas utilizando diferentes distancias de separación entre puntos: 0,005 m, 0,01 m, 0,05 m, 0,1 m, 0,25 m, 0,5 m, 1 m y 2 m. Se calcularon nuevos modelos de regresión con los datos muestreados obteniéndose buenas estimaciones de los parámetros para todos los conjuntos de datos.

Palabras clave: dendrometría, nogal, láser escáner, *convex hull*, agricultura de precisión.

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1. Introduction

Juglans regia L. (walnut) is one of the most valuable trees for timber, used in the furniture industry and also for its seeds (fruit). It is widely grown in China, US, Eastern Europe and the Middle East. Its area of cultivation has been duplicated in Spain during the last decade, covering an area of 12000 ha in 2015 (MAAM, 2015). This tree species is also used in urban green spaces. Its large crown, height and leaves mean that it has an important role in the urban ecosystem (Chianucci *et al.,* 2015). The crown of the tree is quite irregular what makes difficult their parametrization from measurements taken at field, especially for large trees.

The assessment of logging has been traditionally based on dendrometry, measuring variables such as stem diameter, height, crown diameter, which allow to estimate the available timber, wood quality, and fruit production. In addition, dendrometry has been used to assess the influence of urban forests and individual tree species on the carbon cycle and the reduction of greenhouse gases. This represents an active research topic (Manes *et al.,* 2012). Specific surveys on urban forests have been carried out to expand the domain of multipurpose forest inventories (Corona *et al.,* 2012). Standard field methods are limited because certain parameters cannot be retrieved with accuracy, mainly from the crown. Crown volume of trees derived from standard field methods is time consuming and of low accuracy. For this reason, this parameter is not usually estimated using methods based on measurements taken in field. However, previous studies have reported the importance of crown volume and crown area to pruned biomass estimation (Fernández-Sarría *et al.,* 2013a; Estornell *et al*., 2015). It is difficult to measure this parameter in field directly. Diameters are usually measured to characterize the crown but this parameter is of low relevance to analyze its role in different systems, such as, its effect in the microclimate in urban areas, fruit production or water needs in agriculture, and wood quality in forestry. So far, actual crown volume has been the great unknown to manage these trees. This has led to the use of high-level technologies to automatize and optimize operations and performance. For example, among the various existing techniques, indirect optical methods have been widely used to estimate leaf area index, including foliar and woody materials from measurements of radiation transmittance through the canopy (Chianucci *et al.,* 2015).

Another alternative to dendrometric manual data is given by three-dimensional data acquisition using a Terrestrial Laser Scanner (TLS). Terestrial Laser Scanning is an active remote sensing system that works by measuring the time delay from when a pulse is emitted by the sensor to when it bounces back from the object. The returned energy is analyzed as a function of time. Thus, knowing the time and the speed of the laser propagation, the distance between the sensor and the object can be derived. From the coordinates of the TLS station and the vertical and horizontal angles, which can be obtained in a TLS system, the position of each point is calculated (XYZ coordinates). TLS allows capturing more than a million points per second with millimeter precision. The structure of the tree can be retrieved with accuracy offering highly detailed information of branches and leaves distributed in the canopy. In addition, a TLS system has the advantage of reducing uncertainties in inferring some forest parameters such as above-ground biomass (Calders *et al.,* 2015). There is a growing body of literature that recognizes the importance of TLS in agriculture. Several studies have reported that this technology has relevant potential in agricultural applications: drift detection (Gil *et al.,* 2013); monitoring growth stages (Hosoi and Omasa, 2009); crown volumes for quantifying pesticides and to inventory the potential of residual biomass to be transformed into biofuels (Rosell *et al.,* 2009a; Keightley and Bawden, 2010; Fernández-Sarría *et al.,* 2013a). This technology can be implemented in dynamic mode VLS (Vehicle Laser Scanner), enabling continuous data and integration with GPS, an inertial measurement unit and odometer data (Rosell *et al.,* 2009b; Miranda-Fuentes *et al.*, 2015) and in static mode (several scans from different positions around the trees, Moorthy *et al.,* 2011) what can be very interesting for modelling trees with irregular or large crowns or for unique or heritage trees. The point clouds obtained are processed through specific routines that manage the three-dimensional data, allowing filtering of anomalous points, subsamples, integration with spectral information, generation of crown volumes fitted to points, and measurements of height, diameter, volume, etc. (Miranda-Fuentes *et al.,* 2015) in both tree and herbaceous crops (Rosell and Sanz, 2012; Höfle, 2014; Tilly *et al.,* 2014).

A significant aspect of using TLS data is the size of the files that are generated. The huge volume of data and the lack of optimized methodologies led to develop new approaches and algorithms to increase the effectiveness of TLS technologies keeping the accuracy. In this sense further research is required to ascertain what is the most suitable density of data to retrieve fruit trees parameters and thus make measurement and processing operations more efficient from a computational and storage point of view.

The aim of this work is to develop regression models to predict crown parameters for walnut trees using a TLS system: crown volume, total height, crown height and crown diameter. It was evaluated if there was a good correspondence between standard field methods and TLS technique to estimate crown volume, which are difficult to obtain from standard field methods. Also, this research studied the influence of the point density on the detection and characterization of trees, with the aim of optimizing resources and accuracy.

2. Material and methods

2.1. Field data

This study was conducted in Viver (Valencian region of Spain) which has a typical Mediterranean climate: warm, dry summers (22°C) and mild winters (7°C). The average annual rainfall is 550 mm. The average elevation was 588 m above sea level. A set of 30 *Juglans regia* L. was randomly selected under leaf-on condition covering a wide range of sizes (crown diameters from 3.02 m to 10.82 m). All sampled trees are cultivated for nut production. They were in full production stage. Although trees of this species can have huge dimensions (crown diameter greater than 10 m and 25-30 m high), trees located in orchards and focused on nut production usually are smaller.

Total height (Ht), crown height (Hc) and crown diameter (Dc) were measured at field (Table 1): Ht was measured by a pole considering the distance between the apex of the tree and the ground; Hc was calculated by the difference of total height and the distance between the first branch of the crown and the ground; Dc were derived as the average of two diameters measured in N-S and E-W directions using a measuring tape. In addition crown volume was retrieved using as a surface model a paraboloid solid (equation 1).

$$V_p = \frac{1}{2}\frac{\pi \cdot Dc^2 \cdot Hc}{4} \qquad (1)$$

Being, V_p (m^3) the paraboloid volume used to model the nut tree crown, *Dc* the crown diameter (m) and *Hc* the crown height (m).

Table 1. Statistics of the walnut tree parameters measured in field.

	Hc (m)	*Ht* (m)	*Dc* (m)
Average	3.56	4.31	5.23
Standard Deviation	1.16	1.20	1.91
Minimum	2.02	2.52	3.02
Maximum	6.84	7.24	10.82

Hc, crown height in m; *Ht*, total tree height in m; *Dc*, crown diameter in m.

2.2. Laser scanner data

The walnut trees were scanned in June of 2015, coinciding with the field campaign and using a FARO® Laser Scanner Focus3D. The characteristics of this device are shown in Table 2. The trees were measured using four positions for small-medium trees and five positions for larger trees. The distance between each tree and the TLS was around 6 m. In this way, all trees were scanned completely from each side. An average of five reference targets (spheres) was used on each tree to register each point cloud measured from each position. The maximum and minimum error for this process was between 1.5 mm and 3.6 mm what can be considered acceptable for this study. Faro Scene Software (version 5.4.4.4) was used to process and manage laser scanner data. The point clouds were clipped for each tree, the terrain points were removed manually and for each isolated tree a file was created. Additionally two more files were generated manually for each tree containing the stem points and the crown points. Original data were subsampled using a distance of 2 mm. A set of three representative trees of the study can be seen in Figure 1. From these data, crown volume (Vc_{TLS}), total height (Ht_{TLS}), crown height (Hc_{TLS}) and crown diameter (Dc_{TLS}) were retrieved. These parameters were obtained from routines developed with Matlab® (version R2010b. MathWorks, Inc.).

Table 2. Characteristics of the TLS instrument (FARO® Laser Scanner Focus3D).

Technical parameter	Value
Range Focus3D 120	0.6 – 120 m
Ranging error	± 2 mm at 25 m
Measurement speed	up to 976,000 points·s^{-1}
Field of view	305°
Step size (vertical/horizontal)	0.009° (40.960 3D pixel in 360°)
Max. Vertical scan speed	97 Hz
Weight	5.2 kg
Laser power (CW)	20 mW (laser class 3R)
Wavelength	905 nm
Beam divergence	0.19 mrad (0.011°)
Beam divergence at exit	3.0 mm, circular
Size	240×200×100 mm
Scanner control	via touchscreen display and WLAN

To calculate the crown volume (Vc_{TLS}) the convex hull algorithm was applied. This method is based on the definition of the boundary of a three-dimensional closed convex surface generated by Delaunay triangulations. This surface is composed by triangles formed from the external points of the crown cloud data. The algorithm, implemented in Matlab, removes the points that are within the boundary of the convex hull (i.e. interior points). To do this, firstly, six exterior points of the cloud data (maximum and minimum X, Y, Z) were selected to generate an irregular octahedron and the outside points were divided into eight separated regions for each side. Next, the point with the longest distance to the plane formed by an octahedron side was selected in each region. A new figure of 14 vertices (six initial points and another eight ones from the second step) was created. Twenty-four new triangles were formed between the vertices and the points within the new figure were removed. Then, the previous steps were iterated selecting new points whose distances to the new triangle sides were maximum and generating new polyhedrons until there were no points outside of the geometrical figure. The convex hull was obtained from the irregular polyhedron with *n* sides generated in the last step and its volume was calculated.

The total tree height (Ht_{TLS}) was obtained using the file that contains the tree cloud. It was calculated as the difference in Z coordinate between the highest (top) and the lowest (ground) point. The height of the crown (Hc_{TLS}) was obtained calculating the difference between total tree height and the first branch of the tree. This branch was identified selecting the point with the minimum height in the file that contained crown points.

To obtain the crown diameter (Dc_{TLS}), firstly, all points of the crown were projected on a horizontal plane. Then, it was obtained the center of the projected crown considering the central point among the top points of the stem. Then, five steps were applied to determine the diameter: a)

Figure 1. Representation of three walnut trees representative of this study.

polar coordinates were determined between the center point and each contour point; b) 72 circular sections were defined every 5°; c) within each section, all radii were calculated and it was selected the longest one; d) to obtain the diameters, it was added the selected radius of the first section (extracted from the section 0°-5°) and the radius of the 180° section with respect to the first section (between 180° and 185°). All diameters were calculated similarly obtaining 36 diameters, each one for 5° circular section; e) the crown diameter of a tree was calculated as the average of the maximum diameter and its perpendicular one.

The statistics of the tree parameters calculated from TLS data i.e. total height (Ht_{TLS}), crown height (Hc_{TLS}), crown diameter (Dc_{TLS}) and crown volume (Vc_{TLS}) can be seen in Table 3. All the parameters derived from TLS data were used as potential explicative variables in the regression models to estimate field parameters.

Table 3. Statistics of the parameters of walnut trees derived from TLS data.

	Ht_{TLS} (m)	Hc_{TLS} (m)	Dc_{TLS} (m)	Vc_{TLS} (m^3)
Average	4.37	3.91	5.63	87.69
Standard Deviation	1.22	1.04	2.02	106.88
Minimum	3.06	2.69	3.37	13.49
Maximum	6.99	6.29	10.77	383.76

2.3. Estimation of parameters

To estimate every field parameter (*Ht*, *Hc*, *Dc*, V_p), step wise regression models were calculated by considering the set of potential variables derived from TLS data (Ht_{TLS}, Hc_{TLS}, Dc_{TLS}, Vc_{TLS}). Multicollinearity was analyzed in the models by means of Variance Inflation Factor (VIF) value. In case of models with more than one variable, a VIF value larger than 5 was set to remove a potential independent variable (Belsley, 1991). The validation of every parameter estimated was done by leave-one-out cross validation technique through a comparison of the root mean squared prediction error (RMSEcv). This parameter was compared to the root mean square error of the regression (RMSE). Similar values between RMSEcv and RMSE indicate the capability of the calculated model to estimate walnut trees.

2.4. Density data analysis

To analyze if coarser point cloud densities can be used to estimate walnut trees parameters, all point clouds were subsampled to the distances of 0.005 m, 0.01 m, 0.05 m, 0.10 m, 0.25 m, 0.5 m, 1 m and 2 m. Then, all the TLS parameters were derived for each resolution and new regression models were calculated. To identify the most suitable point cloud density, the models were compared by RMSE and R^2 parameters using as reference values those obtained with the highest resolution (0.002 m). In addition, the relative RMSE (per cent) was calculated as the relation between the RMSE of the model and the mean value of the parameter measured at field.

3. Results and Discussion

3.1. Crown diameter

As can be shown in Table 4, the best model to estimate *Dc* was obtained when Dc_{TLS} was selected as the explicative variable. In this case, R^2 value was 0.95. Only one variable explained the majority of variability of crown diameter. The results of cross-validation indicated a low difference between RMSE, 0.43 m, which represents 4% of the Dc average measured at field (%RMSE = 4.0%) and RMSEcv, 0.47 m, (%RMSE = 4.4%). A strong correlation was found among predicted values obtained from cross-validation and field data, $R^2 = 0.94$ (Figure2). These results reveal the good performance of TLS data to predict crown diameters. Good results were also obtained ($R^2 = 0.92$) when crown volumes derived from TLS were selected as independent variables (Table 4). In comparison to other studies, slightly lower results ($R^2 = 0.91$) were obtained for *Platanus hispanica* (Münchh.) trees. This could be explained by the fact that a lower number of stations were used in this case and the larger size of the trees made it more difficult to acquire field measurements in an urban environment (Fernández-Sarría *et al.,* 2013b). For olive trees, similar results were obtained in terms of R^2 (Moorthy *et al.,* 2011) which indicates the potential of this technology to obtain primary tree structure parameters.

Table 4. Parameters of the crown diameter regression model.

Parameter	Estimate	Standard error	*P*-value	R^2	Rcv^2	RMSE	RMSEcv
Constant	0.046	0.240	0.8482	0.949	0.936	0.438	0.473
Dc_{TLS}	0.919	0.040	0.0000				
Model	$Dc = 0.046 + 0.919 \cdot Dc_{TLS}$						
Constant	3.725	0.131	0.0000	0.919	0.892	0.551	0.619
Vc_{TLS}	0.017	0.001	0.0000				
Model	$Dc = 3.725 + 0.017 \cdot Vc_{TLS}$						

Dc: crown diameter of walnut trees (m); independent variables derived from TLS data: crown diameter (Dc_{TLS}), crown volume (Vc_{TLS}); root mean square error in m (RMSE); cross validation root mean square error in m (RMSEcv); cross validation determination coefficient Rcv^2.

3.2. Total height

A good relationship between field data and TLS-based total height was obtained, $R^2 = 0.95$ (Table 5). This result indicates the good potential of TLS data to estimate this parameter too. The validation analysis indicates a good agreement between RMSE (0.27 m, relative RMSE = 6.3%) and RMSEcv (0.28 m, relative RMSE = 6.5%). A distribution of predicted *vs*. field values close to the line 1:1 can be observed in Figure 2. A strong relationship was also obtained when crown height calculated from TLS data was selected, with values of R^2 and RMSE, 0.89 and 0.40 m, respectively (Table 5). Moorthy *et al.* (2011) obtained similar results in terms of R^2 for olive trees. A slightly lower value of R^2 (0.87) was obtained for *Platanus hispanica*

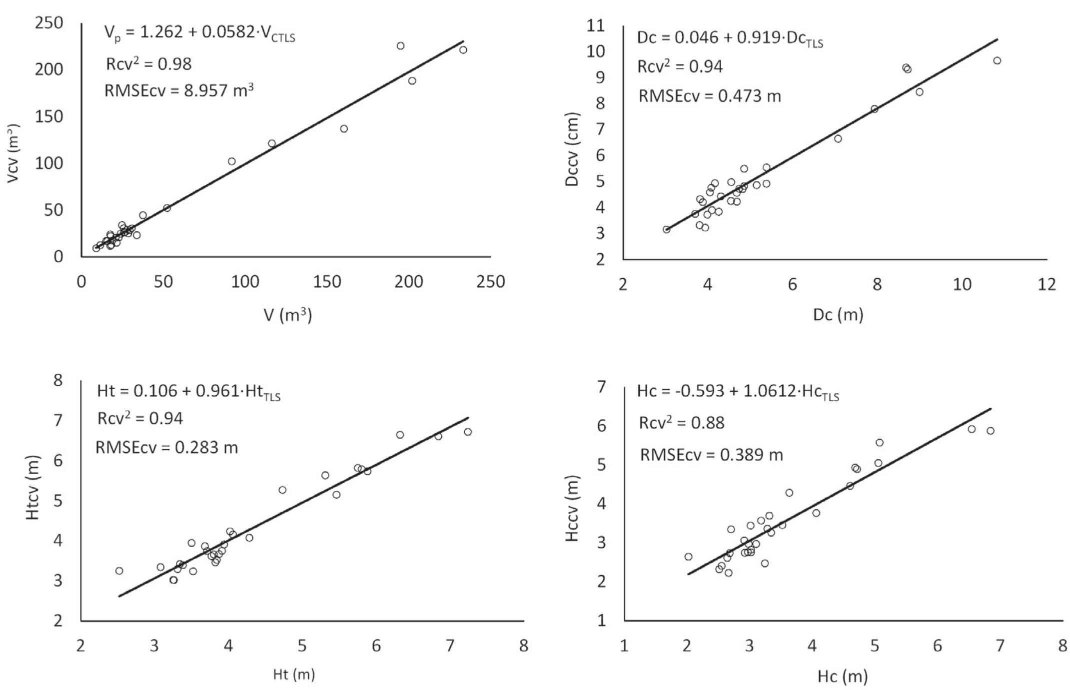

Figure 2. Comparison of field and predicted values after applying cross-validation for each parameter: *V,* crown volume in m^3; *Dc*, crown diameter in m; *Ht,* total height in m; *Hc*, crown height in m. The *cv* parameters correspond to the same parameters obtained in the cross validation processes.

Table 5. Parameters of the total height regression model.

Parameter	Estimate	Standard error	*P*-value	R^2	Rcv^2	RMSE	RMSEcv
Constant	0.106	0.187	0.575	0.951	0.942	0.271	0.283
Ht_{TLS}	0.961	0.041	0.0000				
Model	$Ht = 0.106 + 0.961 \cdot Ht_{TLS}$						
Constant	0.025	0.287	0.930	0.894	0.882	0.397	0.405
Hc_{TLS}	1.095	0.071	0.0000				
Model	$Ht = 0.025 + 1.095 \cdot Hc_{TLS}$						

Ht: total height of walnut trees (m); independent variables derived from TLS: total height (Ht_{TLS}), crown height (Hc_{TLS}); root mean square error in m (RMSE); cross validation root mean square error in m (RMSEcv); cross validation determination coefficient Rcv^2.

(Münchh.) (Fernández-Sarría *et al.,* 2013b). In this case, these differences could be explained by considering the height of these trees, which are larger and thus it was more difficult to measure their apex.

3.3. Crown height

The regression model calculated for this parameter gave an R^2 value of 0.90 and RMSE of 0.36 m, which represents 10% of the Hc average measured at field (Table 6). This lower accuracy for this parameter compared to the rest of variables was also found in other studies (Fernández-Sarría *et al.,* 2013a; Moorthy *et al.,* 2011). This result could be explained by taking into account the fact that the crown height is calculated as the difference of two values: total height and the distance from ground to the first branch, thereby accumulating errors of two measurements. The RMSEcv (0.39 m) value was similar to the RMSE (0.36 m), which indicates the validity of the calculated model to estimate crown height. The same conclusions can be drawn by observing the good fit among predicted values and field measurements for this parameter (Figure 2). Good results were also obtained when Ht_{TLS} was selected as the independent variable, $R^2 = 0.90$ and RMSE = 0.39 m (Table 6).

3.4. Crown volume

Regression analyses indicated a strong relationship between paraboloid crown volumes and volumes derived from TLS data (Table 7). In this case the RMSE was 7.710 m^3 (relative RMSE = 14.7%). It should be highlighted that for this parameter the relative RMSE was larger in comparison to the rest of the tree parameters. This result could indicate that crown volume was calculated with lower accuracy using standard field methods, which are only based on the crown height and crown diameter (Paraboloid volume). In contrast for TLS, the distance among points was 2 mm allowing to define the irregularities of the crown with detail. The results of the validation analysis show a close agreement (Table 7, Figure 2). High accuracy was also obtained when crown diameters derived from TLS data were selected as explicative variables (Table 7). The possibility of modeling the crowns in three dimensions is particularly interesting for agriculture applications such as pruning and spraying. These results are comparable in terms of

Table 6. Parameters of the crown height regression model.

Parameter	Estimate	Standard error	*P*-value	R^2	Rcv^2	RMSE	RMSEcv
Constant	-0.593	0.263	0.032	0.905	0.882	0.363	0.389
Hc_{TLS}	1.0612	0.065	0.000				
Model	$Hc = -0.593 + 1.0612 \cdot Hc_{TLS}$						
Constant	-0.373	0.261	0.164	0.896	0.866	0.378	0.416
Ht_{TLS}	0.899	0.057	0.000				
Model	$Hc = -0.373 + 0.899 \cdot Ht_{TLS}$						

Hc: crown height of walnut trees (m); independent variables derived from TLS data: crown height (Hc_{TLS}), total height (Ht_{TLS}); root mean square error in m (RMSE); cross validation root mean square error in m (RMSEcv); cross validation determination coefficient Rcv^2.

Table 7. Parameters of the crown volume regression model.

Parameter	Estimate	Standard error	*P*-value	R^2	Rcv^2	RMSE	RMSEcv
Constant	1.262	1.833	0.4968	0.985	0.979	7.710	8.957
Vc_{TLS}	0.582	0.013	0.0000				
Model	$V_p = 1.262 + 0.0582 \cdot Vc_{TLS}$						
Constant	-117.336	8.318	0.0000	0.943	0.9319	15.166	16.215
Dc_{TLS}	30.1248	1.392	0.0000				
Model	$V_p = -117.336 + 30.1248 \cdot D_{CTLS}$						

V: crown volume of walnut trees using a paraboloid model (m^3); independent variables derived from TLS: crown diameter (Dc_{TLS}), crown volume (Vc_{TLS}); root mean square error in m (RMSE); cross validation root mean square error in m (RMSEcv); cross validation determination coefficient Rcv^2.

accuracy with the results reported by Fernández-Sarría *et al.* (2013b), thus indicating the potential of TLS data to define the crown volume of trees.

3.5. Density data analysis

As can be observed in the Figures 3 and 4, the values of R^2 and RMSE are practically the same for a cloud subsampled distance from 0.002 m to 1 m. In contrast, the number of points decreased significantly from 128,629,778 to 2320, respectively. These results indicate that lower point cloud resolutions can be used to estimate nut parameters without losing accuracy, thus increasing efficiency in terms of computing costs and data storage. For subsampled distances greater than 2 m it was not possible to define tree crowns due to the reduce number of points per tree. When the distance among points was 2 m, a moderate decrease was detected in terms of R^2 and RMSE for total height. In contrast, for crown volume, the accuracy parameters remained high for all the subsampled distances.

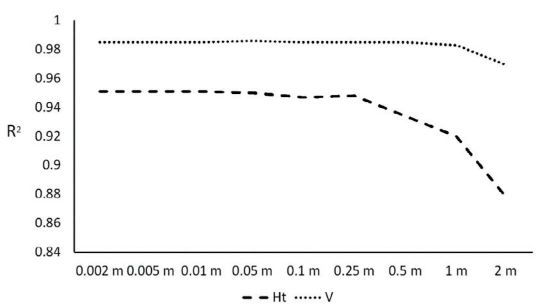

Figure 3. Determination coefficient variation for total height (*Ht*) and crown volume (*V*) estimation for subsampled distances from 0.002 m to 2 m.

4. Conclusions

Models to predict parameters of walnut trees were obtained with high accuracy from TLS. There are no species-specific models for TLS-based data available for walnut trees. It was demonstrated the strong relationship between walnut tree parameters retrieved by TLS technique and parameters derived from field measurements, even for those

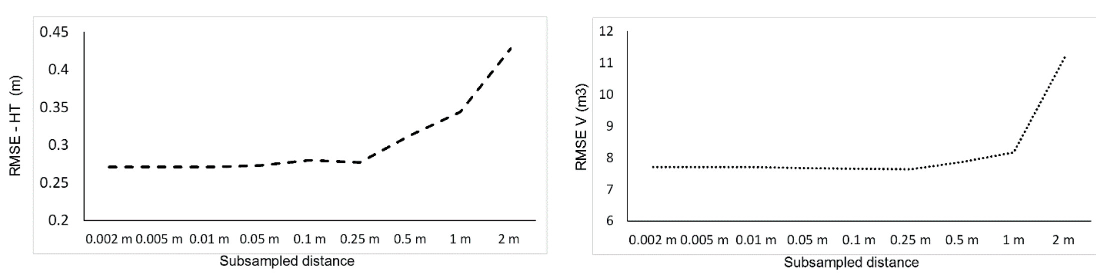

Figure 4. Variation of RMSE for total height (*Ht*) and crown volume (*V*) estimation for subsampled distances from 0.002 m to 2 m.

that are not easy to obtain from standard field methods like crown volume. However, differences between volumes calculated from TLS and field data lead to consider the TLS volume, allowing the definition of 3D-crown with high detail (spacing points 0.002 m), as a new parameter with high potential to retrieve biophysical variables of walnut trees such as pruning biomass and production. In addition, TLS models obtained offer enough accuracy to obtain field data, which are usually applied in walnut surveys and management operations. Therefore, TLS allows to obtain a new parameter of reference, crown volume, and the traditional data in the same operation. Models used in this study could play an important role to calibrate tree parameters obtained by standard field methods or other LiDAR techniques as ALS data (Greaves *et al.,* 2015), being this last system more suitable for large areas.

The results indicate that a lower density of scanned points can be used to estimate dendrometric parameters in walnut trees without reducing their accuracy, what supposes increasing efficiency in terms of computing costs and data storage. It should be remarked that walnut trees were registered under leaf-on conditions and further research would be necessary to study how the absence of leaves might decrease the number of points needed to estimate the parameters of these trees.

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