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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 (TLSs) 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 *P. hispanica*, to help improve their management, especially the quantification of residual biomass.

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 (DTMs), digital surface models (DSMs), 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

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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 and Menq, 1995), construction (Arayici, 2007), civil engineering (Riveiro et al., 2011; Slattery et al., 2012), cultural heritage (Guidi et al., 2004), criminal investigation (Cavagnini et al., 2007; Sansoni et al., 2009), forestry and agricultural applications (Moorthy et al., 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, 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; Diéguez et al., 2003). Dendrometry has been usually based on the proportionality principle of the structure sizes, which are a characteristic of species (Velázquez-Martí et al., 2011c). The relationship between crown volume and biomass was pointed out in Forrester et al., 2012 or Velázquez-Martí 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 leaf area index (LAI) and leaf area density (LAD) 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/s). 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 Fig. 1.

2.1. Field data collection and processing

For this work 30 urban trees of *P. 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 (Fig. 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.