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Ph.D. thesis

INDIRECT METHODS FOR RESIDUAL BIOMASS MEASUREMENT COMING FROM PRUNING OPERATIONS OF URBAN FORESTS

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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 these resources is conditioned, by the amount of existing biomass within urban community ecosystems. This research was focused on direct and indirect quantification of lignocellulosic waste from urban tree pruning. The treated species, *Morus alba, Platanus hispanica, Sophora japonica, Phoenix canariensis* and *Phoenix dactilifera* are widely deployed as ornamental vegetation in Mediterranean countries. Mathematical models for predicting the available amount of pruning residues for each species were developed from easily measurable dendrometric parameters, such as diameter at breast height, crown diameter, total tree height, obtaining coefficients of determination between 0.67 and 0.96. These models can be used for urban inventories and the application of logistic models. On the other hand, Terrestrial Laser Scanner (TLS) technology was applied to improve the estimates of tree architectural parameters obtained by ground-level observations at individual tree level. For this, apparent crown volume was calculated by 4 different methods: *global convex hull* for the entire point cloud that forms the crown; *convex hull by layers* of 5cm height in the XY plane; triangulation by XY flat *sections*, and discretization of the point cloud in small elements of volume (*voxel*). Finally, residual biomass for each species was classified and characterized according to the UNE norms, including dimensional analysis of the obtained materials, density, moisture content, calorific value as well as carbon, nitrogen, hydrogen, and sulfur content. Models to predict the gross calorific value from the elemental composition were developed for fast indirect determination in industry.

RESUMEN

Una gran cantidad de biomasa residual con posible uso energético e industrial puede ser extraída de las operaciones de gestión de los árboles ornamentales de las ciudades. La rentabilidad del aprovechamiento de estos recursos está condicionada por la cantidad de biomasa existente en los ecosistemas urbanos. Esta investigación se ha centrado en la cuantificación directa e indirecta de los residuos biomásicos de la poda de árboles urbanos ornamentales. Las especies estudiadas fueron *Morus alba*, *Platanus hispanica*, *Sophora japonica*, *Phoenix canariensis* y *Phoenix dactilifera* las cuales son ampliamente utilizadas como vegetación ornamental en los países mediterráneos. Modelos matemáticos para la predicción de la cantidad residuos de poda disponible han sido desarrollados para cada especie a partir de parámetros dendrométricos de fácil medición, tales como diámetro del tallo a altura del pecho, diámetro de copa o altura total, resultando coeficientes de determinación entre 0.67 y 0.96. Estas ecuaciones pueden ser utilizadas para los inventarios urbanos y la aplicación de los modelos logísticos. Por otra parte, se han analizado técnicas de escaneado con láser terrestre (TLS) para mejorar las estimaciones de los parámetros dedrométricos de árboles existentes, y relacionarlos también con esta biomasa residual obtenida. Para ello se han calculado los volúmenes aparentes de la copa con 4 métodos diferentes: *global convex hull* para la nube de puntos que forma toda la copa, *convex hull por capas* de 5cm de altura en el plano XY, triangulación por secciones planas XY y discretización de la nube de puntos en los pequeños elementos de volumen (voxel). Finalmente, la biomasa residual de cada especie fue clasificada y caracterizada de acuerdo con las normas UNE incluyendo análisis de las dimensiones de los materiales obtenidos, densidad, humedad, poder calorífico, contenido de carbono, nitrógeno, hidrógeno y azufre. Modelos para la predicción del poder calorífico superior a partir de la composición elemental han sido desarrollados, para su determinación rápida en la industria de forma indirecta.

RESUM

Una gran quantitat de biomassa residual amb possible ús energètic i industrial pot ser extreta de les operacions de gestió dels arbres ornamentals de les ciutats. La rendibilitat de l'aprofitament d'estos recursos està condicionada per la quantitat de biomassa existent en els ecosistemes urbans. Esta investigació s'ha centrat en la quantificació directa i indirecta dels residus biomásics de la poda d'arbres urbans ornamentals. Les espècies estudiades van ser *Morus alba, Platanus hispanica, Sophora japonica, Phoenix canariensis* i *Phoenix dactilifera,* les quals són les àmpliament utilitzades com a vegetació ornamental en els països mediterranis. Models matemàtics per a la predicció de la quantitat disponible de residus poda han sigut desenrotllats per a cada espècie a partir de paràmetres dendromètrics de facil medició, tales com el diàmetre de la tija a l'alçada del pit, diàmetre de copa o alçada total de la planta, resultant coeficients de determinació entre 0.67 i 0.96. Estes ecuacions poden ser emprades per l'elaboració d'inventaris urbans i l'aplicació de models logístics. Per altra banda, s'han analitzat tècniques d'escanetjat amb làser terrestre (TLS) per mijorar les estimacions dels paràmetres dedromètrics d'arbres existents, i relacionar-los també amb esta biomasa residual obtinguda. Per allò s'han calculat els volums aparents de la copa amb 4 mètodes diferents: *global convex hull* per al núvol de punts que forma tota la copa, *convex hull* per capes de 10 cm d'alçada en el pla XY, triangulació per seccions planes XY i discretización del núvol de punts en els xicotets elements de volum (voxel). Finalment, la biomassa residual de cada especie va ser clasificada i caracteritzada d'acord amb la norma UNE incloent analisis de les dimensions dels materials obtiguts, densitat, humetat, poder calorífic, contingut de carbó, nitrógen, hidrógen i sofre. Models per la predicció del poder calorífic superior a partir de la composició elemental ha sigut desenvolupada, per la seua determinació ràpida en la industria de forma indirecta.

NOMENCLATURE

Symbol	Unit
mm	millimetre
cm	centimetre
m	meter
g	gram
kg	kilogram
cal	calorie
%	percentage

Symbol	Meaning
ALS	Airborne Laser Scanning
B	dry biomass (kg)
ba	bark (%)
C	Carbon (%)
ch	crown height (m)
CHM	digital crown height models
D	wood density (g/cm^3)
dbh	diameter at breast height (cm)
dc	crown diameter (m)
dl	large end diameter at the lower end of a section (cm)
dm	diameter midway along a section (cm)
do	base diameter of a branch (cm)
dob	diameter over bark (mm)
DSM	digital surface models
DTM	digital terrain models
du	small end diameter at the upper end of a section (cm)
dub	diameter under bark (mm)
f	form factor
GCV	gross calorific value (kJ/kg)
H	Hydrogen (%)
hc	distance from soil to the crown (m)
h	total tree height (m)
h_s	separation between sections (cm)
K	proportional factor between the paraboloid volume and hemisphere
l	length of a branch (cm)
ls	length of a section (cm)
LAI	leaf area index
LIDAR	Light Detection and Ranging
MAE	mean absolute error
M_{ar}	moisture content of biofuel (%)
m_1	mass of empty drying container (g)
m_2	mass of drying container and sample before drying (g)
m_3	mass of drying container and sample after drying (g)
m_4	mass of packaging moisture (g)
N	Nitrogen (%)
R^2	coefficient of determination
S1, S2	areas of the consecutive sections
S	Sulfur (%)
sd	standard deviation
sdf	standard deviation of form factor
TLS	Terrestrial Laser Scanning
V	volume of a branch (cm^3)
V_c	volume of a section (cm^3)
Vg	green volume (cm^3)
VLIM	Voxel-based Light Interception Model
VLS	vehicle-based laser scanning
Vgs	volume of a geometrical solid of same diameter and height (cm^3)
V_r	real volume of a section (cm^3)
v_m	model volume (cm^3)
vc	apparent crown volume (m^3)

W	oven-dried weight of wood (g)
W 10	up to 10% moisture content in wet basis (%)
X	coordinate
X_m	coordinate of the centre of the trunk
X_{min}	minimum value of X coordinate in the X plane
X_{max}	maximum value of X coordinate in the X plane
X_{pc}	coordinated of each point in the X plane
Y	coordinate
Y_m	coordinate of the centre of the trunk
Y_{min}	minimum value of Y coordinate in the Y plane
Y_{max}	maximum value of Y coordinate in the Y plane
Y_{pc}	coordinated of each point in the Y plane
Z	coordinate
Z_{min}	minimum value of Z coordinate in the Z plane
Z_{max}	maximum value of Z coordinate in the Z plane
ρ	distance from center of the trunk to a scanned point in the plant

1. INTRODUCTION

It is known that vegetation of urban, leisure, industrial and communication areas plays significant ecological, scenic and aesthetic functions, contributing to improving the quality of life in the urban surrounding. While urban vegetation was used primarily as a tool for ornamental purposes, it is important nowadays to focus on its role in environmental improvement. Few studies have estimated the impact of urban forest wood on environmental quality, among others the amount of residual biomass, which can be used to achieve ecological and energy targets. Due to routine care of urban greenery and planned changes in spatial structure of green areas within urban community ecosystems, waste is produced in form of woody parts that are an annually renewable resource.

It is estimated that urban tree wood originating from pruning operations is a potentially abundant, underutilized source of biomass that could contribute significantly more to regional and national bio-economies than it does at present. More effective utilization of wood residuals from urban areas, could offer bio-based fuels for heat and power generation, reduce pressure on forests, decrease waste disposal costs and land take up on a local and regional level (MacFarlane, 2009). The volume of generated lignocellulosic waste varies greatly, depending on the species, type and frequency of pruning practice, and other factors (Saiz de Omeñaca et al., 2004). Generally, the availability and characteristics of urban tree biomass, relationships between tree parameters and quantity of material yielded during management operations are not well documented.

Currently, municipalities are forced to destiny a relevant percentage of their budgets for the maintenance of urban green space. Nevertheless, only a minor share of woody residuals is being recovered. Few processes are applied to generate income that can offset the expenses of this operation (McKeever et. al, 2003, USDA, 2002). A great share of urban wood ends up in landfills (MacFarlane, 2007). Some woody residuals are recovered for composting, recycling or other uses (McKeever et. al, 2003). Moreover, the lack of precise information on the basic characteristics of species in relation with potential biomass is a barrier to the rational use of this material and the achievement of social benefits. Due to the above, there is a high necessity to create a comprehensive database on residual biomass from urban trees, which would enable to create and implement solutions that are both economically and environmentally attractive. To popularize the use of biomass from ornamental trees, to reduce maintenance outages in urban and recreation areas, it is necessary to specify the amount and characteristics of the material obtained.

In the urban zones, the development conditions of vegetation vary significantly from those that can be found in rural and forest areas. Due to the existence of buildings and pavement, solar irradiation, wind speed, air humidity and shading, a specific urban microclimate is generated, simultaneously influencing parameters such as the rate of growth and crown shape. Numerous studies have analyzed the costs, benefits and carbon storage capacity of urban forests. Nevertheless, these studies are limited by the lack of research on urban tree residual biomass. Moreover, the estimates of carbon storage in urban environments mainly rely upon allometric relationships developed for trees in traditional forests (McPherson et al., 2001, Pataki et al., 2006). More exact quantification of urban wood biomass depends on development of allometric relationships especially for urban trees. Reasons exist to believe, that allometry associated with traditional forests does not accurately represent urban systems. Characteristics such as low tree density in urban environments, connected with the potential competition for resources are one important point (McHale et al., 2009). Growing in an open environment, urban forests frequently receive additional water and nutrient supply. In North America, studies have shown, that urban trees, including those located in areas considered as stressful, noted higher rates of trunk growth comparing to published rates for the same species in traditional forests. It is concluded that this fact is due to a possible result of release from competition and above average precipitation (Rhoades et al., 1999). Trees in urban settings have different challenges comparing to those located in traditional forests such as damage, disease and pruning. The results indicate that soil moisture, air temperature, relative humidity, leaf temperature and vapour pressure deficit were less favourable for urban trees.

Direct tree biomass measurement by felling is accurate but time-consuming, expensive and forbidden in many environments. For this, destructive sampling is substituted with every time more adequate, indirect methods. Plant structure investigation is now focused on the possibility of replacing ground-level labor-intensive inventory practices with modern remote sensing systems. 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. This technology can be a new observational tool for precise characterization of vegetation architecture within natural and plantation-like environments. Introduced for applications in urban forests, allows three-dimensional modelling and geometrical characterization of trees, making it easier to develop management systems based on precise information.

The objective of this research was to study the possibility of using lignocellulosic residual biomass from urban forests, particularly as a renewable energy source or raw material for industry. For this, the study was focused on: direct biomass quantification removed under specific pruning operations; development of lignocellulosic biomass prediction models based on allometric relationships between tree dimensions and yielded biomass; development of methods of TLS point cloud processing to determine tree architecture; residual biomass estimation by TLS and ground observations; comparison of tree dimensions and crown volumes obtained with both methodologies; characterization of physical and chemical properties of materials for energy and industrial applications.

2. LITERATURE REVIEW

Urban forestry is defined as "*the art, science and technology of managing trees and forest resources in and around urban community ecosystems for the physiological, sociological, economic and aesthetic benefits trees provide society*" (Helms, 1998). Pruning is a horticultural practice that involves selective removal of undesired, diseased, damaged, dead or structurally unsound plant parts. Reasons to prune urban trees include deadwood removal, shaping, improving or maintaining health, reducing risk from falling branches or aesthetics (Galan Vivas et al., 2011). Clark et al., (2010) calls pruning the heart of arboriculture and one of the most important services that arborists provide. As pruning is a wounding process, that causes a certain level of injury to trees, it is important to limit it to the amount, which is necessary to accomplish the pruning objective. Correct pruning, can extend the life of urban trees, improve their safety and increase their value. On the other hand, improper pruning can damage a tree, decrease its value and make it hazardous. As pruning is also one of the most visible management actions provided on trees in the urban environment, it is important to make it a wise investment.

2.1. CHARACTERIZATION OF PRUNING CONDITIONS AND TECHNIQUES IN URBAN FORESTS

Gil-Albert (2001) describes five main conditions why trees should be pruned namely: technical conditions, aesthetic and landscape conditions, urban conditions, sanitary conditions and safety conditions. These are described below:

2.1.1. Technical conditions

According to which are the goals of pruning operations, these can be classified into:

a) Cleaning technique of pruning

Cleaning techniques of pruning, involve all types of pruning operations, where the main objective is to eliminate undesirable elements such as: hazardous, dead, dry, damaged or insect-infested branches and parts of trees, misdirected or crossed branches, branches located too close to each other or to the tree trunk. Also selectively are removed some epicormic branches, leaving those which demonstrate good development in desired directions. This leads to an increased airflow and development of a strong tree structure, as well as helps to eliminate conditions, that could cause risk to people and properties. These types of operations are necessary for all trees, for any age, species, location or dimensions (Gil-Albert, 2001).

b) Formation technique of pruning

Formation techniques of pruning, are all types of pruning operations, whose goal is to give a tree a certain shape, form. Unless man intervenes, trees according to their habitat and vegetative characteristics, adopt an aspect that is called natural. This can be variable. The most representative are globular forms, pyramidal or lobed. While the asymmetrical forms or parasol-shaped are more frequently evolved by human. The formation technique of pruning mainly focuses on the formation of the trunk, axis, skeletal branches and election of trunk height (Gil-Albert, 2001).

c) Maintenance technique of pruning

Maintenance techniques of pruning are all pruning operations, held in order to maintain the tree in good conditions for long periods of time (Gil-Albert, 2001).

d) Renewal technique of pruning

Renewal techniques of pruning, are operations by which undesired parts and elements of a tree, are removed in order to replace them with new and younger ones (Gil-Albert, 2001). This type of pruning is performed to improve the appearance, form and structure of trees that have been damaged, vandalized or pruned in a drastic way like topping. Restoring a tree usually requires a number of pruning interventions over a period of years.

Frequently formation techniques of pruning are identified with young trees, maintenance techniques with adult trees and renewal techniques with old trees (Gil-Albert, 2001).

2.1.2. **Aesthetic and landscape conditions**

When the tree is left to grow freely, it naturally takes a form characteristic of the species. However, man is able to guide its development and obtain a completely different shape, do to pruning and regular maintenance. The main objectives of pruning when taking to account aesthetic and landscape conditions are:

- A simple regulation of the natural shape of a tree,
- A set of formation and maintenance pruning techniques, in order to obtain artificial shapes (Michau, 1987).

A simple regulation of tree shape, such as formation of tree form, crown dimensions, the appearance and height of tree trunk, total tree height and tree density, allows gaining perspective and transparency.

When pruned according to specific geometric shapes, trees are involved in creating a certain landscape, hiding undesirable and unaesthetic views (Drenou, 2006, Gil-Albert, 2001).

2.1.3. **Urban conditions**

The urban green space, including tree-lined streets and avenues, as well as public parks, faces many limitations. First and most important, is the available space. The proximity of houses and narrow sidewalks often makes the tree exceed the desired space. The consequences of lack of space in some situations, may lead to lack of aeration and lighting. Moreover, the proximity of trees to windows and balconies provokes miner visibility and increased sensibility to vandalism and theft. Other limitation is the total height of urban tress. Very tall trees interfere with electrical networks and are more sensible to wind, what increases the risk of falling branches. Other reason leading to pruning operations are the visibility of traffic lights, street lamps and traffic signs, which cannot be covered by vegetation. Vehicle traffic mainly in case of buses and large trucks is another factor that requires certain trunk height and level of branches (Gil-Albert, 2001).

2.1.4. **Sanitary conditions**

Pruning can sometimes fight specific diseases or pests.

2.1.5. **Safety conditions**

The public nature of urban forests including roads, the presence of property and goods placed under the trees, as well as the traffic density, impose on the responsible institutions to guarantee satisfactory safety conditions for all involved users. For this, dead, damages and hazardous branches and other parts of the trees, must be removed regularly, to reduce injury or property damage risk (Drenou, 2006, Gil-Albert, 2001).

2.1.6. **Pruning palm trees**

Palm trees have a different anatomy and form than broadleaf evergreen, conifers and deciduous species. For this reason, they require special pruning. Basically, only dead fronds should be removed, while the elimination of live fronds should be limited to those that are severely chlorotic or broken. Moreover, palm fruit, flowers and loose petiole base should be removed, if considered to be a safety risk (ANSI A300, 2001). From a biological point of view, it is not convenient to prune palm trees, as the fronds contribute to better protection against cold, wind and salt. Mature fronds feed the fruit, new fronds and roots. Cutting vigorous green fronds, not only reduces the photosynthetic capacity of the plant and with it, the force of the tree and the capacity of producing young fronds, but also produces an unnecessary mobilization of reserves stored in the palm stipe (Del Cañizo, 2002). For this, their removal is very harmful. The motivations of pruning palms are essentially aesthetic, cultural and for safety reasons. Correct pruning of palm species should consist of keeping the highest number of live fronds. This allows protecting the terminal bud at the apex of the stipe, retaining a maximum amount of reserves, and mechanically supporting the young fronds (Drenou, 2006). When pruning palm trees, it is important not to use using climbing spurs (also known as hooks, spurs, spikes, climbers), in order to avoid wounds on the stipe and the spread of *Fusarium oxysporum* (Del Cañizo, 2002). It is also important, to disinfect pruning tools before and after pruning, in order to avoid transmitting disease-causing organisms on tools (ANSI A300, 2001).

2.2. URBAN FOREST BIOMASS ESTIMATES

Urbanization is increasing, and has the potential to increase in a greater scale in the years ahead. Many areas, with rapid urban expansion, are altering and displacing forests, agricultural areas and other value open spaces. As urbanization of landscapes increases, so does the importance of urban forests, their impact on local, regional and global environments and influence on great majority of population (Nowak et al., 2005). Planning and managing forests in and near urban areas, has been most affected by the urbanization process (Konijnendijk, 2000). Urban tree and woody yard residuals form an important component of the municipal solid waste stream. Some woody residuals are recovered for composting, recycling and other uses. Nevertheless, a significant amount is discarded. It is estimated that the total amount of tree and woody yard residuals, form a resource, as large as the timber harvest in National Forests in the United States. Both sources are not interchangeable, as the urban residuals are suitable for low value products such as mulch, while forest timber for high value solid wood and pulp products (McKeever et al., 2003).

Urban biomass research is commonly conducted at coarse scales that include entire cities and regions. There is lack of focus on individual tree biomass (McHale et al., 2009). Jenkins et al., (2004) observes that estimates of dry weight biomass of trees and particular tree parts are of great interest to managers, policymakers and researchers. A research by Pillsbury et al, (1998), notes that the urban forest inventories should describe composition, structure and volume of urban trees. For this, data should be collected on tree parameters, such as diameter at breast height and total tree height in addition to species location, health or damage rating. McFarlane (2007) notes, that wood biomass from urban zones is an extensive, rather than intensive resource, although land clearing and destructive weather events can lead to an increased amount in short periods of time. The research also points out, that the logistics of collecting and utilizing residual biomass is incomparable with harvesting from point sources such as plantations (McFarlane, 2009).

The concept „urban forest'' is defined differently across countries what makes it difficult to operationalise for the purpose of resource inventories (Konijnendijk, 2003). FAO (2002) reports, that „trees outside forests'' need to be uniformly described for better integrated and sustainable management. Following Konijnendijk et al., (2005), the characterization and assessment of urban forests in European cities and towns is a complicated task as few data exist or have been published and no comprehensive inventory seems to be available at the moment. Information on urban green space cover in Europe has been based on few surveys, varies depending on author and includes assessment for only selected European cities. The European Environment Agency (EEA) (1995) estimates the urban forest surface within municipal boundaries between 5% (Madrid) and 60% (Bratislava), while Pauleit et al. (2002) at the level from 1.5% (Thessaloniki) up to 62% (Ljubljana). Ottitsch (2002) points out an average of approximately 30% (5%-56%) or 6-7000 m^2/inhabitant of green space for 14 surveyed European cities. In a research by Konijnendijk (2001), average woodland cover within municipal boundaries of 26 larger European cities is estimated at 18.5% (104 m^2/inhabitant). Spain is estimated to have between 0.8 m^2/inhabitant (Pamplona) and 39.2 m^2/inhabitant (Vitoria-Gasteiz) with an average of 8.95 m^2/inhabitant, respectively (Observatorio de la Sostenibilidad en España, OSE, 2009). In 2012 the population of EU-27 reached 503.5 million people of which in Spain 46.2 million people (Esurostat, 2012). This would give a number of 413.5 million m^2 of urban green areas in Spain and 52364 million m^2 in Europe. The city of Valencia has an approximate surface of 4.6 million m^2 of green areas that can be exploited as a source of biomass generated in the pruning and maintenance of plant species (Urribarrena, 2011). This biomass is calculated at the level of 4518 tones/year (OAM, 2012) of mixed material or 0.98 kg/m^2 year. Other research (Siuta, 2000), reports 5 t/ha year of green mass in Poland. In a study held in Oklahoma, USA, biomass dry matter yields of urban green waste are quantified as: lawn detaching between 4245-7220 kg/ha, lawn mowing 125-765 kg/ha, tree pruning (mulberry) 1905-2520 kg/ha and leaf raking (mulberry) 305-1640 kg/ha, respectively. The calculated quantity was dependent on annual precipitation and month of maintenance operations (Springer, 2012). All authors express concern about data comparability and quality, issuing problems as different green space categories and lack of record and inventories of urban tree resources (Konijnendijk, 2003). Lack of data at national and international level has also been a result of different levels of planning and management hierarchy as well as variety of owner structures. On the other hand, a number of examples of well developed inventory and management systems exist in larger cities. However, even those rarely include private and commercial spaces that present a significant proportion of urban tree population. There is also little data on composition and characteristics of urban forests. A survey by Pauleit et al. (2005) show, that green space cover varies significantly across the countries. European Environment Agency (EEA) (2010) demonstrates a lower share of urban green space in the south and west of the continent. Besides quantitative differences, Pauleit et al. (2005) observe differences in species composition depending not only on climatic zones but also local planting policies. This research demonstrates, that Northern-European cities have lower diversity of species due to harsh climatic conditions comparing to Central and Western Europe. In the last, despite a broad selection of species, at least 50% of street trees represent three to five genera. Other research proves that parks, gardens and road alignments of the cities are characterized by a large number of different species, what makes it complicated to quantify the potential energy value for Spain and Europe. In case of Valencia are found 214 different species of trees (Samo Lumbreras et al. 2001).

Care, maintenance and renovation of green spaces requires removing grass, foliage of trees and shrubs, branches, entire trees and shrubs, harvest from vines and hedges, herbaceous and waterside vegetation, all at different stages of vegetation, various moisture content and some partly decomposed. The quantity of removed biomass is proportional to the health and growth intensity of vegetation and depends mostly on soil fertility, irrigation, climatic conditions and frequency of maintenance operations. Systematic removal of organic material from urban green areas decreases soil fertility and eventually its productivity (Siuta, 2000, OAM, 2012). Depending on country, these looses are compensated by use of external origin compost and mineral fertilization (Siuta, 2000) or by mulching extracted biomass and leaving it *in situ* (OAM, 2012). In most cases, plant mass is treated as one stream, loaded into containers and transported to landfills. Only in some cases it is used for composting, biogas production, fertilization or solid biofuel production such as pellets and briquettes. Pruning is held to maintain the highest standing biomass and only remove dangerous or damaged parts, what makes it impossible to estimate a mean weight of concrete materials, and energy value specific to the material. Due to differences in biomass treatment, management policies, environmental awareness, accessible technology and economical background, the quantity of plant mass removed under pruning will significantly vary on local, national and international level. Best information will be held by greenery companies, waste management companies and landfills. A research by Blokhina et al. (2011) argues, that landscape management grass is mostly harvested late, resulting in unfavourable composition for many utilization purposes. However, biogas production can be a sensible option for using landscape management grass, while the harvesting period is of extraordinary importance as it affects methane yield. Grass is described as a highly inhomogeneous material with extremely variable substrate characteristics (Prochnow et al., 2009). It has been verified, that methane yields decrease with advancing stage of vegetation (Prochnow et al., 2005). This is a result of increasing contents of crude fibre that decreases the maximum biogas production potential, as crude fibre consists mainly of hemicellulose and lignin, both hardly degradable under anaerobic conditions (Prochnow et al., 2005). The biogas yield from fresh green grass is estimated at 520-640 m^3/t VS (El Bassam, 1998). Agricultural and forest residuals can be used for biofuel pellet production. Although the chemical constituents and moisture content of biomass materials vary, due to low amounts of polluting elements and ash (Heschel et al., 1999, Gil et al., 2010) the production of pellets prepared with biomass is becoming a more attractive source of energy (Larsson et al., 2008). The combustion processes of biomass materials are complicated due to highly complex chemical and physical composition, moisture content, density and heterogeneity of these materials. Other disadvantage is the low mechanical resistance of material what leads to high dust emissions, and an increased risk of fire and explosions during pellet handling, storage and transport (Temmerman et al., 2006). Although the combustion characteristics of biomass may vary depending on the composition of the raw material, the use of biomass/coal blends could produce fuel pellets with more suitable characteristics for combustion as coal has a higher carbon content and calorific value in comparison to biomass (Heschel et al., 1999). Few studies have compared different types of biomass for pellet fabrication, taking as main raw material wood residues. Furthermore, the heterogeneity of the raw materials used in pellet and briquette production makes it difficult to estimate their calorific potential. Pellet obtained from residuals proceeding from pruning of fruit species is estimated to have net calorific value 3800-4500 kcal/kg (Fernandez Gonzalez, 2010). The net calorific value of road side green is estimated as 14,1 MJ/kg (FAO, 2004). Gillon et al., (1997), determined the mean calorific values of green twigs, stalks and leaves for 14 broad-leaved species (18.80-21.10 MJ/kg), 5 conifer species (20.29-22.56 MJ/kg) 24 shrub species (18.65-24.59 MJ/kg) 6 grass species (17.05-18.89 MJ/kg), respectively. Castells (2005) reported net calorific value of park residuals and wood slightly above 4000 kcal/kg. *Morus alba* is characterized as medium-quality fuel wood with a calorific value of 4370-4770 kcal/kg (World Agroforestry Center, 2012). To compare, the gross calorific values of most common fuels are: carbon 34080 kJ/kg, coal 15000-27000 kJ/kg, petrol 48000 kJ/kg and vegetable oils 39000-48000 kJ/kg. A research held by Siuta (2000) described the nutrient content in urban green cover organic material (foliage, herbaceous plants, wood chips, twigs, branches, waterside vegetation) in the city of Warsaw at following levels: zinc 22-260 mg/kg dry mass, cadmium 0.1- 0.3 mg/kg dry mass, lead 0,7-25,0 mg/kg dry mass, chromium 1.0-12.0 mg/kg dry mass, copper 1.3-22.7 mg/kg dry mass, respectively. These contents will be city specific and depend on degree of pollution. Garden plants were characterized with 2.34% ash, while dry leaves 3.83% ash (Castells, 2005).

The EU-27 energy production by source in 2009 was the following: 28,4% nuclear, 20,4% solid fuels, 18,8% natural gas, 12,8% crude oil, 18,3% renewable energy (Eurostat, 2012). While within the primary production of renewable energy in 2009, biomass and waste were at the level of 67.7% in EU-27 and 47.9% in Spain (Eurostat, 2012). The percentage of biomass proceeding from pruning operations is not specified. Nevertheless, biomass is the leading source of renewable energies in EU-27 and green spaces residuals could play a significant role in the future.

Numerous studies have analyzed carbon storage capacity, physical and biological costs and benefits of urban vegetation, improvement of air quality, pollution reduction, energy conservation, noise reduction, effects on ozone and hydrology, as well as social and economic benefits related with urban trees (Akbari, 2002, McHale et al., 2009, Johnson et al., 2003, Nowak et al., 2007). These studies have been limited by lack of research on urban tree biomass (McHale et al., 2009) and direct measurement of urban tree volume (McPherson et al., 2001, Pataki et al., 2006). In most research, urban tree wood biomass estimates were done for whole aboveground biomass, using models for forest-grown softwoods and hardwoods. Forest-derived biomass equations overestimate biomass from urban species (Nowak, 1994). Equations used in biomass prediction normally use parameters such as diameter at breast height, tree height and crown dimensions to yield all aboveground biomass estimates. In general, research conducted on urban settings has been limited (Peper et al., 1998). Variables that affect tree growth as site characteristics (soil, water etc.) and climatic conditions are different among cities, what causes that allometric relationships will vary (McHale et al., 2009 Eamus et al., 2000, Kuyah et al., 2012). Management practices also influence biomass production and allocation within trees in landscape (Keith et al., 2000, Ong and Huxley, 1996). Droppelman and Berlier, (2000) argue that pruning may affect the rate of biomass accumulation as cutting and pruning can change biomass without changing dbh. For that, allometric equations based on dbh should be refined by including height, wood density, or crown area to improve accuracy (Ketterings et al., 2001, Chave et al., 2005). At the moment, studies concentrated on developing methods for predicting and quantifying residual biomass proceeding from pruning operation of urban trees seem unavailable or not published. However, data on characterization of particular tree parts have been reported. Information on total leaf-surface area and leaf dry-weight biomass for open grown urban trees have been based on equations derived from diameter at breast height and crown parameters such as crown height, average crown diameter and average shading factor for individual species (Gacka-Grzesikiewicz, 1980, Nowak, 1996). These studies found, that estimates based on crown width gave lower mean square errors comparing to models based on diameter at breast height. Nevertheless, these data have been obtained for healthy, full-crown open-growing delicious trees and will tend to overestimate leaf area and biomass in cases as pruning (Gacka-Grzesikiewicz, 1980, Nowak, 1996). Other studies estimate crown biomass and leaf area from allometric equations based on sapwood area, diameter at breast height and crown dimensions (McPherson 1998, Turner et al., 2000, McHale et al. 2009, Dobbs et al., 2011). Crown biomass calculations have been based on non-destructive methods as randomized branch sampling, while leaf area on direct methods as foliage and litter fall collection, leaf area index and destructive sapwood measurement (Turner et al., 2000, Dobbs et al., 2011). Dobbs et al., (2011) developed branch biomass equations with R^2 from 0.4 to above 0.6 noting, that some of the equations overestimate biomass in smaller trees. This might be a result of faster height growth rates comparing to diameter-growth rates in juvenile trees affecting the diameter-height relation. Peper et al., (1998) listed other indirect methods as the use of aerial imagery and video images.

As a potentially new line of investigation, no commercial or technical equipment for pruned biomass estimation has been found in previous studies.

A study by McHale et al., (2009) incorporated a list with a number of equations derived from other studies, including only those, that represented a measure of all aboveground biomass without leaves and with a large enough diameter range for comparison purposes. The majority of mentioned equations were derived from trees growing in traditional forests and climates that differ from where the equations were applied (Table 1). One study by Pillsbury et al., (1998), developed volume equations for trees in urban environments. Total tree volume, including volume of all stem segments from ground level including terminal branches and bark was determined.

Table 1. Sources for allometric equations used in urban biomass studies (McHale et al., 2009)

Species	Equation	Source Species	DBH Range (cm)	Source
Bur Oak, *Quercus macrocarpa*	QU1	Red Oak	13–129	Brenneman et al. 1978, Ter-Mikaelian and Korzukhin 1997
	QU2	Bur Oak	3–40	Perala and Alban 1994
	QU3	Oak	14–163	Bunce 1968
Silver Maple, *Acer saccharinum*	ACS1	Sugar Maple	6–168	Young et al. 1980, Ter-Mikaelian and Korzukhin 1997
	ACS2	London Plane	15–74	Pillsbury et al. 1998
	ACS3	Silver Maple	5–46	Alemdag 1984
Green Ash, *Fraxinus pennsylvanica*	FR1	White Ash	13–129	Brenneman et al. 1978, Ter-Mikaelian and Korzukhin 1997
	FR2	Green Ash	15–84	Pillsbury et al. 1998
	FR3	Green Ash	3–79	Schlaegel 1984
	FR4	Ash	9–104	Bunce 1968
Honeylocust, *Gleditsia triacanthos*	GL1	General	10–85	Harris et al. 1973, Jenkins et al. 2004
	GL2	General	>94	Hahn 1984
	GL3	Green Ash	15–84	Pillsbury et al. 1998
Little Leaf Linden, *Tilia cordata*	TI1	American Basswood	13–129	Brenneman et al. 1978, Ter-Mikaelian and Korzukhin 1997
	TI2	American Basswood	5–56	Alemdag 1984
Populus sargentii	PO1	Cottonwood	6–32	Standish et al. 1985
	PO2	Cottonwood	>94	Hahn 1984
American Elm, *Ulmus americana*	ULA1	American Elm	5–30	Perala and Alban 1994, Ter-Mikaelian and Korzukhin 1997
	ULA2	General	10–85	Harris et al. 1973, Jenkins et al. 2004
	ULA3	Elm	>94	Hahn 1984
	ULA4	American Elm	5–56	Alemdag 1984
Hackberry, *Celtis occidentalis*	CE1	Hackberry	>94	Hahn 1984
Siberian Elm, *Ulmus pumila*	ULP1	General	10–85	Harris et al. 1973, Jenkins et al. 2004
	ULP2	Sawleaf Zelkova	6–34	Pillsbury et al. 1998
	ULP3	American Elm	5–30	Perala and Alban 1994, Ter-Mikaelian and Korzukhin 1997
	ULP4	Elm	>94	Hahn 1984
	ULP5	American Elm	5–56	Alemdag 1984
Kentucky Coffee Tree, *Gymnocladus dioicus*	GY1	General	10–85	Harris et al. 1973, Jenkins et al. 2004
	GY2	General	>94	Hahn 1984
Norway Maple, *Acer platanoides*	ACP1	Sugar Maple	6–168	Young et al. 1980, Ter-Mikaelian and Korzukhin 1997
	ACP2	Sugar Maple	3–66	Bickelhaupt et al. 1973, Tritton and Hornbeck 1982

2.3. METHODS TO DETERMINE THE ENERGY POTENTIAL OF BIOMASS

There are three standard methods to analyze energy potential of biomass namely elemental, proximal and structural analysis.

2.3.1. Elemental analysis

The elemental analysis is one of the most important factors when studying the properties of biofuels. The elemental composition of biomass is complex and contains six major organic elements and at least ten inorganic elements important for ash characterization as well as traces of heavy metals (Demirbas, 2003). With the analysis of the percentage of N (nitrogen), S (sulfur) and Cl (chlorine) can be assessed the impact of the use of biomass. While from the concentration of C (carbon), H (hydrogen) and N (nitrogen), can be determined the Heating Value (HV) of biomass.

The C and H are oxidized during combustion by exothermic reaction with the formation of CO_2 and H_2O (Obernberger et al., 2006). Carbon concentration has a positive relationship with Gross Heating Value (GHV) (Callejon et al, 2011, Telmo et al., 2010) justifying major GHV of wood than herbaceous biomass (Obernberger et al., 2006). Moreover, the incensement of the ratio of the sum of C and H in respect to O (oxygen) increases the GCV (Demirbas, 2002). The determination of these elements should be done in accordance with the UNE-CEN/TS 15104:2008. The concentration of C, H, and O in biomass is found in following ranges: 42-71%, 3-11% and 16-49% of mass (Vassilev et al., 2010). The analysis of the concentration of N in biomass is important for environmental protection due to emission of nitrogen oxides during combustion (Khan et al., 2009). Lower values of nitrogen in biomass are found in wood of conifers and deciduous trees comparing to crop residues (Obernberger et al., 2006). Normally the concentration of N in biomass ranges from 0.1 -12% of mass (Vassilev et al., 2010). The determination of N should be done in accordance with UNE-CEN/TS15104:2008. Biomass also contains low amounts of S estimated at 0.01-2.3% of mass (Khan et al., 2009). The determination of sulfur should be done in accordance with ASTM E775-87 (2008).

The main problem of Cl content in biomass is associated with hydrochloric acid frequently deposited on the metal parts of furnaces, stoves and boilers (Demirbas, 2005, Khan et al., 2009, Salmenoja et al., 2000). Its concentration varies for different types of biomass between 0.01 to 0.9%, tends to be scarce in wood and more abundant in straw, cereals and fruit residuals (Khan et al., 2009, Obernberger et al., 2006). The determination of Cl should be done in accordance with ASTM E776-87 (2009).

The ash content in biomass is essential for choosing proper combustion techniques. Wood biomass or horticulture residuals are characterized with low ash content (Callejon et al., 2011, Obernberger et al., 2006). The ash determination is done in accordance with UNE-CEN/TS 14775:2007.

2.3.2. **Proximal analysis**

Proximal analysis consists of the performance of necessary tests to obtain the contents of volatile organic compound (VC), fixed carbon (FC) and ash (Saidur et al., 2011, Khan et al., 2009). The study of these three parameters can be very important for understanding the phenomena of combustion of biomass as they are related to problems as ignition. Moreover, the heating value of biomass increases with higher FC and VC.

Ash is the inorganic and incombustible part that remains after complete combustion. The ash content varies between fuel types, species, plant parts and soil contamination. The available nutrients, soil quality, fertilizers and weather conditions influence the K (potassium), Na (sodium), Cl and P (phosphorus) content. Woody biomass usually is rich in Ca (calcium) and K, while herbaceous biomass often shows high levels of Si (silicon) (Saidur et al., 2011, Demirbas, 2005). The ash concentration in biomass varies from 1% in wood to 30-40% in vegetable waste. Generally, high concentrations of ash decrease the calorific value (Khan et al., 2009, Demirbas, 2004, Demirbas, 2002). The determination of ash should be done in accordance with UNE-CEN/TS 14775:2007.

Biomass usually contains a high content of volatiles. Because of high volatile fraction, biofuels can ignite even at low temperatures and the rapid loss of this fraction makes it necessary to maintain high temperature conditions in order to achieve complete combustion, ensuring efficient and low emission levels (Khan et al, 2009). The volatile organic compound content varies usually between 48-86% of mass in dry basis (Vassilev et al., 2010) and should be determined in accordance with UNE-CEN/TS 15148:2008.

The FC is obtained by calculating the difference between 100% and sum of percentage of mass of ash and VM in dry base (Telmo et al., 2010). This parameter is estimated between 1-38% of mass in dry base (Vassilev et al., 2010).

2.3.3. **Structural analysis**

Biomass contains a variable amount of cellulose, hemicellulose, lignin, a small quantity of lipids, proteins, sugars, water and inorganic constituents (Saidur et al., 2011, Demirbas, 2005). The first three are the most important. The hemicellulose, cellulose and lignin are called lignocellulose. The structural analysis of biomass is highly important to understand the combustion process and determination of GCV (Saidur et al., 2011). Cellulose and hemicellulose are abundant in hardwoods, while lignin is more abundant in softwood. A positive relation is reported between hemicellulose and lignin concentration and GCV (Demirbas, 2001, Demirbas, 2005).

The advantages and disadvantages between the described methods are mostly related to the complexity and necessary time to carry out an analysis.

2.4. LIDAR TECHNOLOGY

LIDAR technology (Light Detection and Ranging) is an active remote sensing system which emits energy that after colliding with objects, returns to the sensor, enabling to measure the distance of objects based on time interval between energy pulse emission and reflection after reaching the targets (round trip) (Moorthy et al., 2011). It enables to record massively information on a 3-dimensional scale from ground-level Terrestrial Laser Scanning (TLS) or Airborne Laser Scanning (ALS). The ALS can record the return signal of a pulse emitted at different echoes and with the help of a GPS and an inertial system, permits calculating the coordinates of the point, where there has been reflection, as well as its intensity (Baltsavias, 1999). The backscattered laser pulse from ALS systems, has been used to extract dimensional parameters such as crown dimensions (Means et al., 2000; Popescu et al., 2008), crown volume (Hinsley et al., 2002, Riaño et al., 2004) and tree height (Andersen et al., 2006; Morsdorf et al., 2004; Hopkinson, 2007; Yu et al., 2004). Also, it enables to define digital terrain models (DTM), digital surface models (DSM) and digital crown height models of vegetation (CHM) with applications for natural resource management (Hudak et al., 2009). It is also used in other multiple areas: geological, morphological and hydrological works, hydraulic modelling (Cobby et al., 2001), building representation (Sohn et. al, 2007), changes in beach sand (Shrestha et al., 2005), fire prediction models and management, as well as forestry applications (Lefsky et al., 1999, Naesset 2002; Maltamo et al., 2006, Popescu et al., 2007). Retrievals from ALS systems, have the advantage of capturing information over a large area, but their laser pulse return density (pts/m^2) is rather low (3-20 backscattered pulses/m^2) (Moorthy et al., 2011). This level of detail is many times insufficient to provide a detailed profile of the vertical axis of a tree crown and bottom parts of vegetation canopies.

Terrestrial LIDAR systems are based on the same principles as the ALS, while having differences in the way of operating. They provide a point cloud, a 3D digital representation of scanned vegetation, in which each point is characterized by an X, Y, and Z coordinate. It permits to work in local coordinates or in a specific reference system. From each station or viewpoint of the instrument, a model is generated, that can be linked to others by marks or homologous identifiable points. Scanning density can become very high, up to 1 point per millimetre. The TLS systems, allow the characterization of the vertical distribution of vegetation structure (Radtke et al., 2001), that could replace manual field inventory practices. These instruments are increasingly used in various applications, ranging from mining, industry, construction, civil engineering, documentation of accidents and criminal investigation, forestry and agricultural applications, etc. In the last field, the information from the TLS can provide a better definition of the structure of vegetation as with this system are obtained data from the whole plant, while the ALS system provides less data of the lower and lateral parts. Moreover, TLS systems have been used to estimate plant area densities (Takeda et al., 2008, Hosoi et al, 2006), ratios of woody to total plant areas (Clawges et al., 2007) and segmentation of tree stem diameters and branching structures (Henning et al., 2006, Hopkinson et al, 2004, Thies et al., 2004). A research by 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. This research claims that LIDAR-based methodologies give the possibility of replacing labour intensive inventory practices in forestry and agriculture. It presents TLS systems as potentially new observational tools for precise characterization of vegetation architecture.

It is possible to combine the information from TLS and ALS, getting data for the entire plant and area. This permits obtaining a good definition of the tree structure and correlating the parameters of the digital model with classic dendrometric data that require slow and laborious measurements (Hollaus et al., 2006).

Numerous studies relate dendrometric variables obtained with traditional instruments with important parameters used in the management of forests (Velázquez et al., 2010), such as pesticide dose optimization (Palacin et al., 2007), knowledge of growth rates and plant productivity (Lee et al., 2009), estimation of biomass of each tree and its use as a physical parameter to indicate tree health status (Lin et al., 2010) or the quantification of waste generated in pruning (Velazquez-Marti et al. 2011a, Velázquez-Martí et al., 2011b). Many studies of TLS data are directed towards obtaining geometric variables of tree crown height, width, surface area and volume (Tumbo et al., 2002, Lee et al., 2009, Moorthy et al., 2011). Some studies argue that ALS systems tend to underestimate total tree height, due to probability of missing tree tops even with high sampling densities (Popescu et al., 2002; Chen et al., 2006). The variable crown volume is one of the most interesting for the management of plantations. Many studies address the problem of crown volume calculation by several methods for different species of tree crops (Wei et al., 2004) and vineyards (Palacin et al., 2008, Rosell et al., 2009). In forest studies, the TLS was also conducted on modelling trees for their comparison with data obtained by airborne LIDAR or classical instrumentation (Kato et al., 2008), analysis of their structure (Gorte et al., 2004, Parker et al., 2004), both in large and homogeneous forest environments (Lovell et al., 2003), and in riparian areas, where equations of resistance to water flows were calculated (Antonarakis et al., 2009).

Some authors use three-dimensional matrix, where the smallest element of information is the voxel (Stoker, 2009). Processing models based on this concept, such as voxel-based Light Interception Model (VLIM) (Van der Zande et al., 2010), can estimate the percentage of incident sunlight that passes through the canopy and determines the LAI (leaf area index) in trees at different stages of leaf growth. With the K-dimensional tree algorithm, point clouds can be discretized in voxels, resampling the data at different resolutions (Park et al., 2010). This method shows several advantages such as

(Stoker, 2009): 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 the trees can be modelled if the laser signal penetrates enough into the tree crown from different stations. Other authors, focused on the division of the point cloud into horizontal or vertical sections, estimating the volumes of the solid within the different sections (Palacin et al., 2007). Moorthy et al., 2011, estimated the volume, deriving from these sections the radius of the circles with the same surface. The work of these authors is particularly noteworthy, given that they also use the convex hull algorithm applied to the flat sections of the point cloud. This algorithm, compared with Savitzky-Golay filter and the values derived from direct field data, is shown as one of the most accurate when studying the growth and productivity of plants (Lee et al., 2009).

Many studies, used laser instruments mounted on mobile platforms known as vehicle-based laser scanning (VLS) in tree crops. However, the accuracy of these equipments is not comparable with the fixed instruments (Lee et al., 2009). Small variations in the distance between the sensor and the tree, as well as the speed of the platform, with slight changes in the shape of the tree, produce errors above 9% in volume calculation. Lin et al., (2010), argues that the TLS is less efficient comparing to VLS, due to laborious recollections when surveying multi-plots of trees. This author claims, that biomass estimation at individual tree level will progress and become less money and time-consuming with VLS systems.

3. OBJECTIVES

3.1. MAIN OBJECTIVE

The aim of this research is to develop methods for indirect quantification of lignicellulosic residual biomass yielded from pruning operations of the mainest Mediterranean urban trees.

3.2. SPECIFIC OBJECTIVES

a) Direct quantification of residual lignocellulosic biomass coming from pruning operations of the following species of urban trees: *Morus Alba, , Phoenix canariensis, Phoenix dactilifera, Platanus hispanica, Sophora japonica*, which are the mainest in Mediterranean areas.

b) Development of lignocellulosic biomass prediction models based on allometric relationships between dendrometric parameters of the trees and quantity of residual biomass.

c) Development of methods of LIDAR data processing from terrestrial scaners to determine dendrometric parameters of the studied species.

d) Analysis between volumetric calculations obtained by terrestrial LIDAR technology and the residual wood biomass from pruning.

e) Characterization of physical and chemical properties of materials in order to evaluate their suitability for energy and industrial applications.

4. MATERIALS AND METHODS

The research presented in this paper is divided into three main blocks:

a) Direct quantification of biomass from pruning and development of mathematical prediction models based on allometric relationships between tree dimensions and quantity of yielded residual.

b) Development of calculation methods of tree architectural parameters and crown volumes extracted from a TLS point clouds. Inter-comparison of analyzed methodologies.

c) Characterization of biomass from an energetic and industrial point of view. Determination of models to predict the calorific value from the elemental composition for fast indirect determination in industry.

4.1. DENDROMETRIC ANALYSIS AND ALLOMETRIC EQUATIONS

The study area was located in the province of Valencia: Alcudia, Alzira, Mislata, Sagunto, Valencia. Taking Valencia as reference, the area is located in latitude 39^{o}28`50`` and length 0$^{o}$21`59``W. The average annual temperature is 17.8^{o}C. Maximum temperatures are observed in August, with the average 25.5^{o}C. Minimum average temperatures reach 11.5^{o}C and are observed in January. Average annual rainfall is 454 mm and relative humidity 65%. The driest period is in July and the wettest in October (www.aemet.es). To perform this study, five ornamental species from the Mediterranean urban forests were selected namely: *Morus Alba*, *Phoenix canariensis*, *Phoenix dactilifera*, *Platanus hispanica, Sophora japonica*. The procedure of trial consisted of a random selection of municipal streets with dense car and pedestrian traffic and city parks and n =30 trees per species. Best effort was made, to obtain highest sample range possible. Within the studied species, each sampled group was randomly selected and is represented by widest size range possible to obtain in cooperation with maintenance companies. Previously to carrying out tree management operations, took place the identification of the selected sample trees. Field data sheets used in the trials are shown in the annex.

Following information was obtained during field research:

a) General information: species, variety, location and province. Moreover, contact data: name of the person in charge, address, telephone number and email. All information was collected in an interview with the person responsible for the management operations.

b) Tree management information: date and type of last pruning operations, tree identification number, diameter at breast height, crown diameter, distance from soil to the crown, total tree height and weight of pruned biomass. Information on date and type of last pruning operations were collected in an interview with the person responsible for the management operations. Trees were numbered sequentially, following the direction of traffic. Tree parameters were measured manually before pruning process started.

Diameter at breast height (dbh) outside bark was measured with a traditional aluminium caliper with precision 0.001 m in small trees or a diameter tape also with precision 0.001 m in big trees at a point 1.3 m above ground level on the uphill side. For trees with elliptical cross sections, the arithmetic average of the long and short diameters was used. Trees that were abnormally shaped, leaning, crooked or forked at or below breast height, were not included in the sample (Husch et al., 2003, West, 2009). The diameter at breast height was reported in cm.

Crown diameter (dc) was measured with a diameter tape with precision 0.001 m and a mirror. Determination of crown diameter at field was complicated due to the irregularity of the crown's outline. For this, the edges of the crown were projected to the ground and next was measured the length along the long and perpendicular axis from one edge point to the other edge point passing through the crown centre. The diameter was determined by averaging measurements of the long axis diameter 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.

Total tree height (h) 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 total height was measured from the base of the tree 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.

Distance from soil to the crown (hc) was determined with a Vertex IV hypsometer with precision 0.01 m. The height was measured from the base of the tree on the uphill side to the base of the tree crown. As a reference for identifying the base of the canopy, the halfway between the first and one or more live branches was taken. The distance from soil to the crown was reported in m (Dieguez Aranda et al., 2003).

Once pruning operations ended, the residual biomass was formed in bundles and weighted by means of a dynamometer with precision 0.01 kg (Figure 1). Weight measurements were carried out in field conditions. Samples of wood were put into small closed plastic containers in order to determine moisture content in laboratory conditions and obtain dry matter results. Where pruning operations were done in the presence of foliage, several branches of each sample-tree were manually defoliated, to determine the percentage of foliage and wood mass. Sample branches were collected for further volume calculations.

Figure 1. From left to right: bundles of pruned branches; weighting process with a dynamometer

4.1.1. **Dendrometric analysis of branches**

The dendrometric analysis is focused on developing methods, to easily calculate the actual volume of particular tree structures. For this, two approaches were carried out: morphic coefficient f (also called form factor) and volume functions were studied.

a) Morphic coefficient f is defined as the ratio between the actual volume and a geometric model volume taken as reference (Equation 1) (Husch et al., 2003). The models that provide the form factor most approximate to 1, best define the shape of the branch.

$$f = \frac{V}{Vgs} \qquad (1)$$

Where
f = form factor
V = volume of a branch (cm^3)
Vgs = volume of a geometrical solid of same diameter and height (cm^3)

The form factor allows determining the volume of any structure by measuring the basal diameter and length. In principle, the form factor should be a parameter characteristic of the species and diameter class. However, for each of the tests performed there is a statistical variability. For this, the mean and standard deviation for each of the cases were determined. The form factor can be influenced by the base diameter and length of the branch. This influence was analyzed.

Actual volume determination was carried out on sample branches collected after pruning operations. To calculate the actual volume, each branch was divided into equal sections with the length of 20cm (Figure 2). The large end, small end and midway diameters of each section were measured by means of a digital caliper with precision 0.01 mm. The volume of each section was calculated applying equations shown in Table 2 (Lopez Serrano et al., 2003; Velazquez et al., 2009; West, 2009). The volume of the whole branch was obtained by adding up all section volumes.

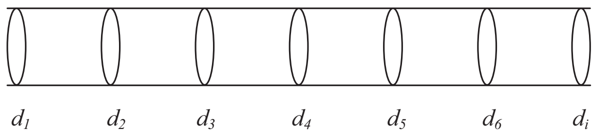


Figure 2. Measurements of diameters in each section

Table 2. Equations for volume of each branch section

Sectional Volume Formulae	Equation for Volume
Huber`s formula	$v_r = \frac{\pi}{4} \cdot dm^2 \cdot ls$
Smalian`s formula	$v_r = \frac{\pi}{8} \cdot (dl^2 + du^2) \cdot ls$
Newton`s formula	$v_r = \frac{\pi}{24} \cdot (dl^2 + du^2 + 4dm^2) \cdot ls$

v_r: real volume of a section (cm^3); dl: large end diameter at the lower end of a section (cm); du: small end diameter at the upper end of a section (cm); dm: diameter midway along a section (cm); ls: length of a section (cm)

Assuming the shape of a branch to resemble a solid of revolution (cone, cylinder, paraboloid and neiloid), the equations used to calculate the model volume of a branch are shown in Table 3 (Husch et al., 2003).

Table 3. Equations to compute volume of solids of revolution

Geometric solid	Equation for volume
Cylinder	$v_m = \frac{\pi \cdot d_o^2}{4} \cdot l$
Paraboloid	$v_m = \frac{1}{2} \frac{\pi \cdot d_o^2}{4} \cdot l$
Cone	$v_m = \frac{1}{3} \frac{\pi \cdot d_o^2}{4} \cdot l$
Neiloid	$v_m = \frac{1}{4} \frac{\pi \cdot d_o^2}{4} \cdot l$

v_m: model volume (cm^3); d_o: base diameter of a branch (cm); l: length of a branch (cm)

b) Regression models were analyzed in order to define volume functions, considering as dependent variable the total volume of the structure (V) and as independent variables the base diameter (d_o) and total length of the branch (l) (Table 4.)

Table 4. Branch volume functions

Author	Equation
Naslund (modif), (Naslund, 1940)	$V = b_0 + b_1 d_0^2 + b_2 d_0^2 l + b_3 d_0 l^2$
Spurr (Spurr, 1952)	$V = b_0 + b_1 d_0^2 l$
Ogaya (Dieguez Aranda et al., 2003)	$V = b_1 d_0^2 + b_2 d_0^2 l$
Hoenald-Krenn (Hohenald, 1936)	$V = b_0 + b_1 d_0 + b_1 d_0^2$

V: volume of the branch (cm^3); d_o: base diameter of a branch (cm); l: length of a branch (cm)

To determine the volume function that provides the best fit, the coefficient of determination (R^2), standard deviation (sd) and mean absolute error (MAE) were calculated. The material used in this trial was a digital caliper and a tape measure with precision 0.01 mm and 0.001 m, respectively.

4.1.2. **Crown volume estimation, biomass prediction models**

Without destructive sampling, the real volume of a tree crown could not be measured. The apparent volume was determined using basic parameters: crown diameter, total tree height and distance from soil to the crown collected during field study. Next, equations for 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 5) (Dieguez Aranda et al., 2003).

Table 5. Growth models of tree crowns

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)

Apparent volume of a tree crown calculated from measurements taken manually at field, was related with data obtained by the TLS and biomass yielded from pruning operations. These tests were performed, in order to verify the accuracy of both methodologies and possible relationship of apparent crown volume with quantity of yielded biomass.

4.1.3. **Statistical analysis**

Following statistical analysis were performed on data obtained in field tests:

Analysis of variance (ANOVA) has been performed to observe if there is a significant difference between the means of analyzed groups. The confidence level used in the tests was 95.0%. Homoscedasticity was verified by analyzing the residual plots generated by the Statgraphics software (Villafranca and Ramajo, 1993). The normal distribution of analyzed groups was also tested by the Statgraphics software by verifying if the skewness and kurtosis values are within -2, +2. In addition, the Shapiro-Wilks test has been performed by means of XLStat software. The ANOVA test allowed studying the influence of several factors on the obtained parameters. For example, in some cases, trees of same species were studied in different location conditions. It was verified, if the location has influence on the residual biomass and dendrometric parameters. Also measurement methods were compared by means of this test.

A variety of regression models were developed in order to predict residual biomass from plant measurement. Regression equations used several explicative parameters, such as diameter at breast height, crown diameter, total height or a combination of these variables. In this study, the outliers have been detected by a specific application of the Statgraphics software. The normality of residuals was verified through residual plot analysis. The independence of residuals was checked by analysis of residual plots or the Durbin-Watson test generated by the Statgraphics software. The goodness of fit of the regression models was studied by the coefficient of determination, standard deviation and mean absolute error. The multiple regression models for each species which gave highest R^2 have been validated. For that, two independent data sets have been organized: one set (n=25) to generate the model and one set (n=5) for its validation. These models are marked with an * and some validation results are attached in the annexes. A t-test has been used to compare the mean of real values and values calculated by a regression model and an analysis of residual plots has been performed.

All statistical tests were performed with Statgraphics 5.1 and XLStat software. It is necessary to emphasize, that the accuracy of developed equations is determined in the context of data used in their construction. There is no guarantee, that these prediction models will apply equally well to an independent sample. Developed regression models will best represent urban forests, where the data were originally collected. Using developed equations in other geographic areas, runs risk of unknown error. Errors may also appear, if the prediction equations are used to estimate biomass of trees, whose parameters values are outside the sample range, or if the tree shape or form deviates significantly from the sample. Nevertheless, the types of equations and influent factors will be similar in all cases. Only it will be necessary to particularize the coefficients from specific trials.

4.1.4. **Studied vegetal material**

In this research five species of Mediterranean urban areas were studied:

a) *Morus alba*

Morus alba L. known as white mulberry is a species of the family *Moraceae*, genus *Morus*. It is native to India and central Asia. Introduced in the VI century in Europe, it is popular in the south of the continent. Reaching up to 15-18 m in height, up to 1.5 m in diameter of the base of the trunk, it is characterized with a broad crown with highly branched long main branches (De La Torre, 2001, www.floraiberica.org). It is a deciduous tree, with big, cordate at the base and rounded to acuminate at the tip leaves. The bark is gray, turning cracked over the years (López Lillo et al., 2006). The flowers are single-sex catkins, with catkins of both sexes being present on each tree. It is characterized with slow growth, resistance to extreme temperatures as well as a strong, resistant to humidity changes and well burning wood. *Morus alba* is cultivated in orchards and as ornamental tree in streets, city parks and towns (López González, 2007).

All sampled trees of *Morus alba* were pruned each year under uniform type of pruning practices. Individuals located on the street, were pruned under topping type of practice, while those located in city parks under annual maintenance type of pruning.

- Topping type of pruning consists of removing a major part of the canopy from the tree and leaving mostly branch stubs (Michau, 1987). Topping is a practice that causes harm to trees and should be avoided. This practice often appears in the urban forests as a consequence of a bad choice of species, lack of space, presence of utility lines, lack of light and risk of accidents do to falling branches (Gil-Albert, 2001). This practice results in the development of epicormic sprouts and unnecessary injuries (Figures 3 and 5).

- Annual maintenance is a light pruning that allows preserving the desired volume and shape of the tree by eliminating the annual sprouting. These operations, if carried out annually in the same spot, after several years, lead to the formation of thickenings at the end of the branch. These thickenings may become necessary to be removed after a few years. Properly done every year, this type of pruning does not provoke problems. In order to avoid the formation of the thickenings, the cut must be done every year some centimetres further on the branch (Michau, 1987) (Figures 4 and 6).

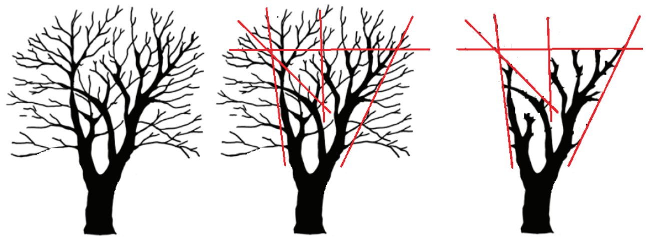


Figure 3. Topping applied to *Morus alba* trees, Bedker et al., 1995 adapted (sheme)

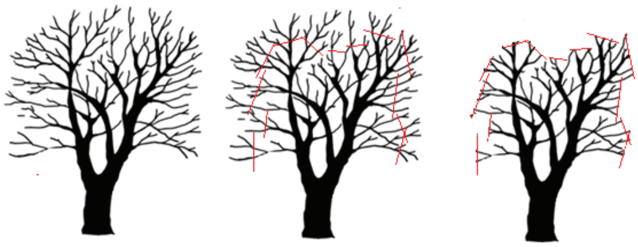


Figure 4. Annual maintenance applied to *Morus alba* trees, Bedker et al., 1995 adapted (sheme)

Figure 5. From left to right: Topping of *Morus alba*: before; after

Figure 6. From left to right: Annual maintenance of *Morus alba*: before; after

b) *Platanus hispanica*

Platanus hispanica Münchh. (*Platanus acerifolia, Platanus hybrida*) is a tree in the family *Platanaceae*, genus *Platanus*. It is thought to be a hybrid of *Platanus orientalis* native to south east of Europe and south west of Asia: Macedonia, Cyprus, north Persia, Afghanistan and the Himalayas, and the *Platanus occidentalis* native to the Atlantic zone of the United States (De La Torre, 2001, www.floraiberica.org). Other authors argue that it may be a cultivar of *Platanus orientalis* (López González, 2007). *Platanus hispanica* is a large deciduous tree that can exceed 30 m in height. The bark is usually pale green, yellow and grey, smooth and exfoliating with characteristic irregular forms. The tree crown is oval in young trees and turns round with age. The leaves are broad, palmately lobed. The flowers are borne in dense spherical inflorescence on a pendulous stem, with male and female flowers on separate stems. The wood is hard, fibrous, resistant and characterized as a good fuel. This species requires light, fertile and fresh soils. 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). *Platanus hispanica* is an extensively cultivated ornamental, parkland and roadside tree in the temperate regions, widely observed in linear plantations in streets as well as isolated in gardens (Ballester-Olmos y Anguís, 2009). It is characterized by a rapid growth, great ease for transplantation and good resistance to pruning operations (López González, 2007, López Lillo et al., 2006).

All sampled trees were pruned each three years under uniform crown raising type of pruning practice. This type of pruning consists of removal of lower branches in order to provide crown elevation clearance for pedestrian and vehicle traffic as well as open views, visibility of lights and signs (Michau, 1987). The lower lateral branches should be cut down systematically every year, but without eliminating more than those that are clearly in excess until the trunk reaches 1.5-2 m in height (Gil-

Albert, 2001). Crown lifting should be performed on young and medium-aged trees. This prevents the low branches from growing to a large diameter. The wounds heal better than in old trees (Bedker et al., 1995). The regulation of the crown elevation is designed to adapt the tree to the different situations where it is situated, as well as to respond to the aesthetic requirements (Michau, 1987) (Figures 7 and 8).

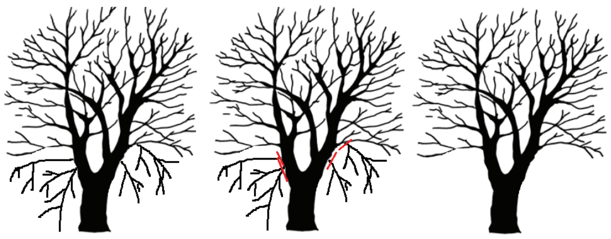


Figure 7. Crown raising applied to *Platanus hispanica* trees, Bedker et al., 1995 adapted (scheme)

Figure 8. From left to right: Crown raising of *Platanus hispanica*; residual transport

c) *Sophora japonica*

Sophora japonica L. also known as *Styphnolobium japonicum* and Pagoda Tree is a species in the family *Fabaceae*, genus *Styphnolobium*. *Sophora japonica* is native to eastern Asia and a popular species in almost all Europe. It is a deciduous, fast growing tree, which reaches up to 25 m in height (www.floraiberica.org). The tree crown is wide and rounded. The bark is dark brown with shallow longitudinal cracks. The leaves are pinnate with 9-13 leaflets. Cultivated as ornamental or shade tree in streets, city parks and towns, often accompanies the *Robinia*, which has a very similar appearance. It is appreciated for flowering in late summer, after most flowering trees have finished and its resistance to cold as well as heat and dryness (López González, 2007). Its beautiful deep green colour foliage is not attacked by insects. The advantage over *Robinia* is to give a denser shade. For this reason, it is widely used in urban zones (De La Torre, 2001).

All sampled trees of *Sophora japonica* were pruned each year under uniform topping type of pruning practice like *Morus alba* . Topping type of pruning consists of removing the major part of the canopy from the tree and leaving mostly branch stubs (Michau, 1987). This practice often appears in the urban forests as a consequence of, lack of space, presence of utility lines, lack of light and risk of accidents do to falling branches (Gil-Albert, 2001). These practices result in the development of epicormic sprouts (Bedker et al., 1995) (Figures 9 and 10).

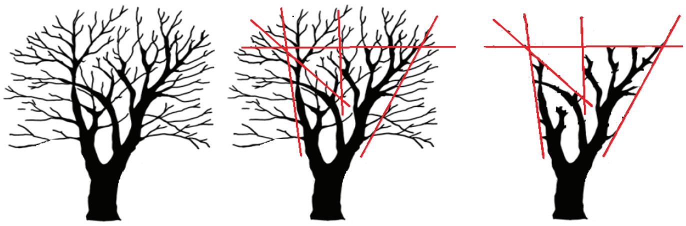


Figure 9. Topping applied to *Sophora japonica* trees, Bedker et al., 1995 adapted (scheme)

Figure 10. From left to right: Topping of *Sophora japonica*: before; after

d) *Phoenix canariensis, Phoenix dactilifera*

Phoenix dactilifera L. (called date palm) and *Phoenix canariensis* hort. ex Chabaud. are species in the palm family *Palmae (Arecaceae)*, genus *Phoenix* (www.floraiberica.org). Palms, posses a number of characteristics, which allow differing them from other plants. The following summary will focus on the characteristics of selected parts of the palm plant.

Trunk

The *Phoenix dactilifera* trunk, also called stem or stipe is vertical, cylindrical and columnar. The girth of the trunk is equal all the way up and does not increase once the canopy of fronds has fully developed. The average circumference is estimated at 1-1.10 m and no ramification is observed. The date palm trunk is brown, lignified and covered for several years with the bases of the old dry fronds that make it rough in touch. With age, these bases obtain smoother appearance with visible cicatrices.

Vertical growth of date palm is provided by its terminal bud, called phyllophor. Data on the height of the trunk differ according to the author and are estimated at 15-20 m and in case of occurrence in their natural environment may reach up to 45 m (Ibañez, 2007; FAO, 2002). However, in case of a nutritional deficiency mainly cause by drought, the terminal bud may experience an abnormal growth resolving in shrinkage of the trunk (FAO, 2002).

Leaves

The date palm has large evergreen leaves that are pinnately or feather-shape compound and spirally arranged at the top of the trunk forming a crown. Their properties differ, depending on variety, age and environmental conditions. An annual formation of new leaves is estimated at the level of 10-26 units and the average life time at 3-7 years. Depending on the distribution within the palms crown, it is estimated that 50% of total leave amount are green and photosynthetically active leaves located on the outside, 40% white juvenile leaves placed on the inside and the rest 10% growing green leaves based in the centre. It is estimated that an adult date palm has 100 to 125 green leaves with the length 3-6 m (FAO, 2002).

The pinnate leaf of the date palm is composed of the following parts:

- the sheathing base or leaf base (this part embraces more or less the trunk, or is attached to it). The sheath consists of white connective tissue ramified by vascular bundles which during the growth of the frond largely disappear. In result, are left dried, brown vascular bundles, a band of tough, rough fibre attached to the lateral edges of the lower part of the midribs of the leaves,
- the leaf stalk or petiole (connecting part between the sheathing base and blade often with no sharp distinction between them),
- blade, rachis or midrib (continuation of the leaf stalk, divided into leaflets which are arranged along both sides in the manner of a feather),
- leaflets (between 120 to 240 per leaf, entirely lanceolate and folded longitudinally. The length of the leaflets varies from 15 to 100 cm and width from 1 to 6.3 cm. Spines may reach up to 20 or 24 cm in length (Del Canizo, 2002; Blombery et al., 1989, FAO, 2002).

In case of palms, sick, old or dead leaves do not drop on their own, but need to be removed under pruning.

Phoenix canariensis also known as the Canary Island date palm is native to Canary Islands. Its stipe reaches 20 m in height and 30-40 cm in diameter. The pinnate leaves have 5-6 m in length (López Lillo et al., 2006). It is widely planted as an ornamental tree in the temperate regions of the world. In comparison with the date palm, the *Phoenix canariensis* has a thicker and shorter stipe, greener and broader leaves (De La Torre, 2001, Ballester-Olmos y Anguís, 1996), as well as much smaller fruit reaching1-2.3 (2.5) cm in length (López González, 2007). *Phoenix canariensis* adapts to different types of soils (Ramoneda et al., 1997). It is resistant to hot and dry environments. Adapts well to drought, for this can be grown in template, subtropical and tropical regions (Jones, 1999).

Both *Phoenix canariensis* and *Phoenix dactilifera* were pruned annually. Annual pruning of palm trees consists of reducing the canopy by removing dead, damaged or unwanted fronds and inflorescences. Sometimes, it is necessary to adapt the dimensions of the palms canopy to the available space. In these cases, fronds that cause problems are removed selectively. It is always important to remove the lowest amount of fronds (Figures 11 and 12).

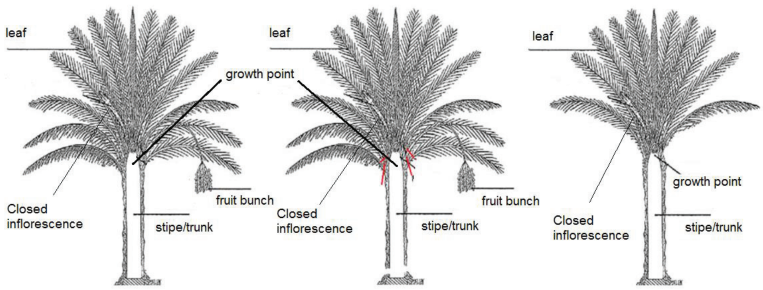


Figure 11. Annual pruning of palm trees, FAO, 2002 adapted (scheme)

Figure 12. From left to right and up to down: Annual pruning of *Phoenix canariensis* before; after*; Phoenix dactilifera* pruning; residuals

Because of large areas where these species are cultivated in Mediterranean urban forests, the quantification and assessment of their residuals becomes important.

4.2. LIDAR APPLICATION

The instrument used in field trials was a Leica ScanStation 2 laser scanner, based on time of flight technology with a dual-axis compensator, high scanning speed (50,000 points per second) and a high resolution camera (www. leica-geosystems.com). Its main technical characteristics are described in Table 6. The equipment consists of the following accessories: laptop, tripod, batteries, aiming marks, etc. (Figure 13).

Table 6. Main characteristics of the equipment Leica ScanStation 2 laser scanner (www. leica-geosystems.com)

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 0-50 m < 1 mm max. Fully selectable horizontal and vertical
Field of view (horizontal / vertical)	360º / 270º	

Figure 13. From left to right: Leica ScanStation 2 equipment with necessary accessories; tripod-mounted HDS target; scanned target

4.2.1. **Field data collection and processing**

In this work 30 sample trees of *Platanus hispanica* were selected in Alcudia, (39º28`50``N, 0º21`59``W), a city located in the province of Valencia (Spain) in the main Av. del Comte Serrallo. This species was selected due to its widespread deployment in urban areas of temperate regions (López González, 2007) and significant volumes of residual proceeding from pruning. The sampled trees were placed on both sides of a road (Figure 14). The width between the tree lines was 12m. The mean distance between trees of the same line was 20 m. This allowed the differentiation between the point clouds of the different trees, which was important for scanning and further processing tasks. Prior to data acquisition a pre-selection of sample trees was made to assure that all individuals would be pruned under uniform crown raising type of pruning practice after the scanning process had finished. Most of the trees were scanned from at least two viewpoints, following a zigzag route to register all sides of each sample tree. Nevertheless, some of them were only scanned from one viewpoint due to trees dimensions, proximity to buildings, etc.

The average age of the studied trees was between 10-12 years. The height was between 8.94 m and 12.8 m, and crown diameter between 4.27 m and 12.12 m. These sizes made it difficult to measure the crown tops of the sample trees with the TLS due to their proximity. Despite these constraints, it is considered that the geometry of the shots was suitable.

Figure 14. Tree distribution

Thirteen stations were used to measure the 30 sample trees. The device was levelled at each station, and after starting the computer, several photographs of the area were taken to define the scanning windows. Then, basic settings of the TLS scanning, such as ambient temperature, atmospheric pressure, and scan resolution (points every 5mm) were selected. In each station, objects or surfaces around the trees were also scanned, such us street, walls, parked or moving vehicles, people (Figure 15).

Figure 15. From left to right: picture of scanned trees in the urban area; obtained scan data, where elements different to the tree must be filtered

Each tree was measured using at least two stations. To merge the different point clouds taken from the different stations, a minimum of 4 point targets or reference marks were measured. These points were used as link points. Next an automatic Registration command was used in Cyclone v.6 software to compute the optimal alignment of the targets so that all of them are aligned as closely as possible. The absolute mean errors of the fitting operations were between 0.003 m and 0.018 m. The error of fitting operations shows how precisely the ScanWorlds and targets are adjusted. After merging data, each tree was recorded in a single file to facilitate processing operations. Scanning data were processed with Cyclone v.6, Leica specific software.

First, the filtrate and removal of unwanted items was made. These are defined as points not belonging to the trees (vehicles, buildings, people, birds, traffic signs, etc.) and which were manually removed with Cyclone v.6 software tool (polygonal fence model-delete inside). Because the fieldworks were conducted over several days and meanwhile precipitation occurred, permanent reference marks in the study area could not been left. Two records were defined, the first among the first 5 stations and the second between the remaining 8. A single point cloud was formed from them.

As an initial idea to carry out the characterization of each tree, it was thought to use various 3D software available on the market. In this way, it was intended that the acquisition of various geometric features could be performed interactively and quick. These tests were carried out using 3DReshaper, Rapidform and Leica-specific Cyclone. Since conventional 3D programs have limited tools, mainly to obtain volumes, some final results were obtained with MATLAB.

4.2.2. **Extraction of tree parameters from TLS point clouds**

The primary tree structure parameters that were extracted from the TLS point cloud were the total tree height, crown height, trunk height and crown diameter. Due to the fact that the TLS permitted to acquire data from different viewpoints, it was feasible to determine tree dimensions from different perspectives. Three files for each tree were made: whole tree (A [No]. xyz), tree trunk (A [No.] T.xyz) and tree crown (A [No.] C.xyz) (Figure. 16). The operator selected manually from the 3D point cloud which points belong to the crown and which points belong to the stem.

Figure 16. From left to right: whole tree (A [No]. xyz); tree trunk (A [No.] T.xyz); tree crown (A [No.] C.xyz)

a) Total tree height

The total tree height was calculated using the A [No.].xyz file. It was estimated using the difference in laser pulse reflection from the top of the crown (corresponding to "peak" of the crown) and the ground (corresponding to the base of the trunk). The result was registered in m.

b) Trunk height

The trunk height was calculated using the A [No.] T.xyz file. It was estimated using the difference in laser pulse reflection from the top of the trunk and the ground (corresponding to the base of the trunk). The result was registered in m.

c) Crown height

When calculating the height of the crown, the difference between total tree height and trunk height parameters was estimated. The result was registered in m.

d) Crown diameter

In order to obtain crown diameter, the average of the longest and the perpendicular diameters was calculated. To analyze the crown diameter, the point cloud was displayed as a projection on the XY plane. A reference point in the form of the center of the trunk was found. This was obtained using trunk specific point cloud (A [No.] T.xyz). All points located within 5cm from the top of the trunk were selected to avoid risk of insufficient point number for the study (Figure 17). The average of X and Y coordinates was calculated, what yielded a reference point for diameter calculation. The reference point is considered accurate, since there is no way of knowing the true central point without destructive sampling. The following figure shows an example of information contained in files that were used for these calculations and the selected area.

Figure 17. A4T.xyz file loaded in Cyclone for trunk centre calculation

For diameter selection, the A [No.] C.xyz point cloud was projected onto the XY plane (Figure 18). Following formulas were applied (Equation 2, 3, 4 and 5):

Increment of X, Y:

$$\Delta x = X_m - X_{pc} \qquad (2)$$

$$\Delta y = Y_m - Y_{pc} \qquad (3)$$

Where:
X_m, Y_m = coordinates of the centre of the trunk
X_{pc}, Y_{pc}= coordinates of each point

Distance from center of the trunk to selected scanned point in the plant:

$$\rho = \sqrt{\Delta x^2 + \Delta y^2} \qquad (4)$$

Angle from the center point to the selected point:

$$\alpha = \mathrm{arctg}\frac{\Delta x}{\Delta y} \cdot \left(\frac{180}{\pi}\right) \qquad (5)$$

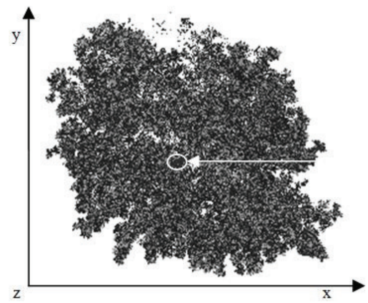


Figure 18. [No.] C.xyz point cloud projected onto the XY plane

This yielded the polar coordinates, assigning to each point a distance and an angle. In the following operations, the value of the angles was changed so that it was between 0^o and 360^o. Next the tree crown positioned at the centre of the trunk was divided into sections with the same centre point and an angle of 5 degrees. This provided a total of 72 sections. The section with the most exterior point was selected (Figure 19). Knowing the angles between each section, all radiuses were calculated. In the event that no radius could be found within the search angle, a new radius was recalculated from the two closest stored radiuses. The diameters were obtained by adding the opposite half of each radius. In this way for the first diameter the radius set between 0° and 5°, and its opposite, between the $180^{th\ o}$ and $185^{th\ o}$ were found and summed. In the same way the rest of the diameters were determined, until a total of 36 diameters were obtained.

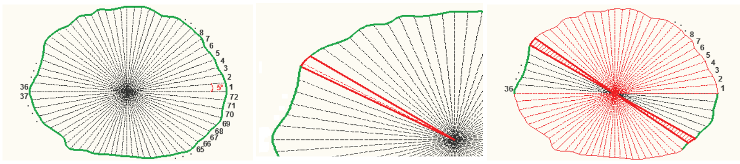


Figure 19. Phases of diameter calculation

The arithmetic mean of the longest (corresponding to section with most exterior point) and perpendicular diameters was considered the crown's diameter for further calculations. It is important to keep in mind, that when applying this methodology in the field, the largest and the perpendicular diameters that are selected may not be accurate. Results obtained with programming will always be more accurate than those obtained manually at field. Furthermore, it should be noted that when measuring crown diameter, the line should pass through the centre point of the trunk. The result was registered in m.

The tree dimensions extracted from TLS point clouds were compared with *in situ* classical dendrometrical measurements applied on the same individuals. This allowed comparing both methodologies by a variety of regression models. To determine models that provided the best fit, the coefficient of determination (R^2), standard deviation (sd) and mean absolute error (MAE) were calculated.

4.2.3. Methods for determination of crown volume

Different approaches to calculate the crown volume were performed. To do this, four processing algorithms were implemented using MATLAB (MathWorks, Inc.). The accuracy and the processing time of each one of them was analyzed (Figure. 20):

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

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

- *Volume calculation by sections* (Method 3): Division of the crown's point cloud into sections of 10cm 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 10cm.

- *Rasterization in voxels* (Method 4): Transformation of the point cloud into small units of volume using a grid in three-dimensional space (voxel).

In Figure 20, the geometrical shapes for crown volume calculation are depicted for each method.

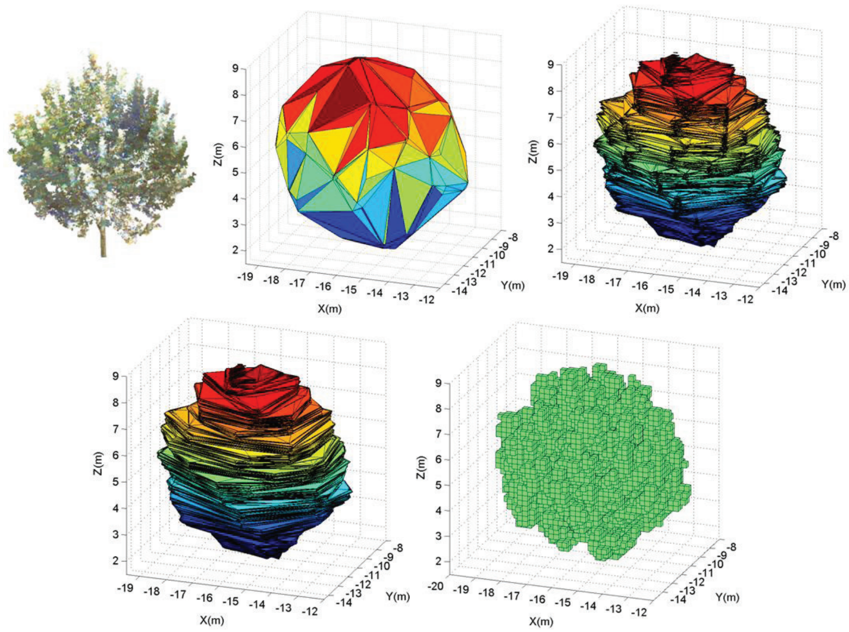


Figure 20. Representation of the four algorithms used to derive crown volume from TLS data. From left to right and top to down: Picture of the scanned crown; global CH; CH layers; triangulation by sections; voxels

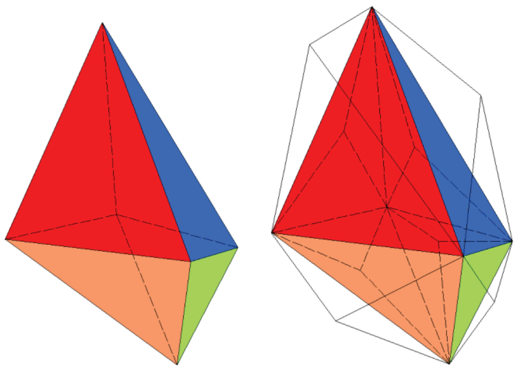
Method 1 *(Global convex hull)*

The convex hull of a set of points in a plane or in a space is the smallest of the areas or volumes that contain the examined points (Graham, 1972). For three-dimensional space, convex hull is the boundary of a closed convex surface generated by 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, Conquer and QuickHull. Of these, was used convhulln function based on the QuickHull algorithm implemented in MATLAB. This algorithm removes the points that are not located in the boundary of the closed convex hull, such as interior points. To do this, the following steps were carried out:

Step 1: Six exterior points of the cloud are selected (maximum and minimum X, Y, Z) generating an irregular octahedron. All points within this polyhedron do not belong to the boundary. The points outside this octahedron are divided in eight separated regions considering each side (Figure 21a).

Step 2: The point with the largest distance to the plane formed by an octahedron side is selected in each region. In this way, 8 new points are selected to generate a new figure of 14 vertexes (6 initial points from step 1 and other 8 from step 2). New 24 triangles are formed between the vertexes (Figure 21b). The points within the new figure are also removed.

Step 3: The previous steps are repeated selecting new points whose distance to the new triangle sides are maximum and generating 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, whose volume can be calculated.



(a) **(b)**

Figure 21. a,b. Initial steps for convex hull formation

The main inconvenience 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 layers*)

This method is based on the same algorithm as Method 1 applied to layers of 5 cm in height.

From the minimum height of the crown, all points located between 0 and 5 cm in height are selected and the convex hull method is applied (Method 1). Then, this method is applied considering the points located between 5 and 10 cm. The process is repeated for every following layer of 5 cm in height. The final volume is obtained adding the single volumes of all layers. The operation number is higher than in Method 1 given that the convex hull function is applied to each layer.

Method 3 (*Volume calculation by sections*)

The tree crown is divided into sections of 10 cm in height. For each section, the section area is calculated. The volume of each section is obtained using the equation 6, where *S1* and *S2* are the areas of the consecutive sections and h_s is the separation between sections (10 cm):

$$V = \frac{S1 + S2}{2} \cdot h_s \qquad (6)$$

Firstly, from the lowest point of the crown's point cloud, all points within 10 cm height are selected. These points form the first section. Within this section, two new sections are formed by points located within 2 cm from top of the section and 2 cm from bottom of the section. Then, a triangulation is applied to the points considered in the same horizontal plane and the area of the section is calculated. This step is repeated for every 10 cm of height of the crown.

Method 4 (*Rasterization in voxels)*

Voxel (*volumetric pixel*), is a minimum discrete volume that can be processed in a tridimensional object (Hosoi et al., 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. The volume of each voxel is added to calculate total volume and the shape of the crown is obtained. To calculate the crown volume considering the voxel concept, the following steps were performed:

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

Step 2. The coodinates X_{min} and X_{max} of first voxel are labelled. Then, all points with coordinates X between those *X-limits* create a set associated to the first sections (S_1) in the YZ plane.

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

Step 4. The coordinates Z_{min}, Z_{max} of the first voxel are also calculated and from points selected in step 3, only those whose *Z* coordinates between those limit values are included in the first voxel *V1*. The coordinates of the voxel *V1* and the presence-absence of points within it are stored in a matrix. The same steps are followed for the rest of voxels *(V2 to Vn)* of the *C1 – S1*. After, this algorithm is applied from the column *C2* to *Cn*. Then this algorithm is applied from *S2* to *Sn*.

The final result is a matrix of coordinates for each voxel indicating presence-absence of points inside. The total volume is obtained multiplying the number of voxels with points inside by the volume of a voxel (80 000 cm^3). The structure of the tree crown can be depicted from the location of each voxel.

The four methods allow the calculation of crown volume and other dendrometric variables such as tree height, trunk and crown height and crown diameter. These variables allow establishing relations with classical manual measurements as well as residual biomass from pruning.

4.2.4. **Volume calculation by classic dendrometry**

The apparent volume of a tree crown can be estimated in terms of its adjustment to 3 geometric shapes of known mathematical formulas, such as a cone, a paraboloid and a hemisphere explained in Table 7. These three forms are used mainly in traditional forests and may misrepresent urban trees, since the development conditions are not the same in natural areas and cities.

Volumes of 30 individuals of *Platanus hispanica* obtained by classical dendrometry and three-dimensional models generated from data recorded by a TLS were compared.

The cone equation and paraboloid equation are proportional, being 2/3 the proportionality factor. Between paraboloid equation and hemisphere there is a relationship (Equation 7), which is dependent on the diameter and crown height. Therefore, this factor is not constant but will show a population variation that is studied in this thesis defining its mean and standard deviation for *Platanus hispanica* trees.

$$K = \frac{2}{3} \cdot \frac{dc}{hc} \qquad (7)$$

Where
K = proportional factor between the paraboloid volume and hemisphere
dc = crown diameter (m)
hc = distance from soil to the crown (m)

On each point cloud, four different algorithms to calculate volumes of tree crowns were applied. These were compared with three geometrical shapes. The method that provided best apparent volume in less processing time and increased automation facing management-related applications was defined.

4.3. WOOD CHARACTERIZATION

4.3.1. Fuel specification

The specification of biomass was based on the norm UNE-EN 14961-1. According to Table 1 of this norm, the classification of the origin and sources of solid biofuel examined in this thesis are the following:

"1. Woody biomass
1.1.Woody biomass from forest, plantation and other virgin wood
1.1.7.Wood from gardens, parks, maintenance of roadsides, vineyards and orchards"

According to the specification of solid biofuels based on shape and properties, the analyzed material is classified as followed (Table 7).

Table 7. Specification of properties of wood logs

Origin: According to paragraph 6.1 and Table 1 of UNE-EN 14961-1.	Woody biomass: *Morus alba* *Phoenix canariensis* *Phoenix dactilifera* *Platanus hispanica* *Sophora japonica*	
Commercial form	Logs, wood	
Dimensions		
Length (L) (maximum length of a single cut), cm	*Morus alba* *Phoenix canariensis* *Phoenix dactilifera* *Platanus hispanica* *Sophora japonica*	L 100+, (max. 380 cm) L 100+, (max. 462 cm) L 100+, (max. 496 cm) L 100, 100 cm ±5 cm L 100+, (max. 180 cm)
Diameter (D) (maximum diameter of a single cut), cm	*Morus alba* *Phoenix canariensis* *Phoenix dactilifera* *Platanus hispanica* *Sophora japonica*	D10, 2 cm ≤D ≤10 cm D10, 2 cm ≤D ≤10 cm D2-, D<2 cm
Humidity (M) (according to received mass)	*Morus alba* *Phoenix canariensis* *Phoenix dactilifera* *Platanus hispanica* *Sophora japonica*	M45 M55+ (Max. 74.82%) M55+ (Max. 71.03%) M45 M45
Volume or weight, m^3 stacked or loose or kg as received	*Morus alba* *Phoenix canariensis* *Phoenix dactilifera* *Platanus hispanica* *Sophora japonica*	Mean dry weight 31.13 kg/street tree; 77.78kg/ park tree Mean dry weight 24.67 kg/tree Mean dry weight 36.13 kg/tree Mean dry weight 23.98 kg/tree Mean dry weight 18.07 kg/tree
Proportion by volume of stumps	*Morus alba* *Phoenix canariensis* *Phoenix dactilifera* *Platanus hispanica* *Sophora japonica*	Whole (unsplit) Whole (unsplit) Whole (unsplit) Whole (unsplit) Whole (unsplit)
Cut surface	*Morus alba* *Phoenix canariensis* *Phoenix dactilifera* *Platanus hispanica* *Sophora japonica*	Smooth and regular Smooth and regular Smooth and regular Smooth and regular Smooth and regular
Wet and rot	*Morus alba* *Phoenix canariensis* *Phoenix dactilifera* *Platanus hispanica* *Sophora japonica*	No No No No No

4.3.2. ***Determination of moisture content***

Moisture occurs in wood in form of free water in cell cavities and absorbed water in cell walls (Husch et al., 2003). The evaluation of drying process was done according to the norm UNE-EN 14774-2. The process took place in two types of conditions. Open-air drying was carried out in laboratory environment with average temperature 21.32ºC and relative humidity 42.41%. A daily record of results took place until the stabilization of weight was obtained. When oven drying, samples were placed on metal trays and located in a stove with controlled temperature (105+-2) °C. The drying time didn't exceed 24h in order to avoid possible unnecessary loss of volatile substances. For sample preparation and result registration an electronic balance was used with the precision of 0.01 g. A number of 30 samples per species were examined.

Total moisture content in wet basis was calculated with the following equation (8) (UNE-EN 14774-2). The results were reported as percentage.

$$Mar = \frac{(m2 - m3) + m4}{(m2 - m1) + m4} \cdot 100\% \qquad (8)$$

Where
M_{ar}= moisture content of biofuel (%)
m_1= mass of empty drying container (g)
m_2= mass of drying container and sample before drying (g)
m_3= mass of drying container and sample after drying (g)
m_4= mass of packaging moisture (g)

4.3.3. **Sample preparation**

To carry out the laboratory analysis the samples were prepared as follow. The analyzed *Morus alba, Platanus hispanica, Sophora japonica* branches were divided into 4 diameter classes and the *Phoenix canariensis* and *Phoenix dactilifera* branches into 3 diameter classes. The diameter classes represent the base of the branch section, midway sections and the upper end section. Next, various wood samples within a diameter section were chipped with a hammermill and stored for laboratory characterization. Within each species and diameter class, convection dried and open air dried samples were tested for calorific value and CHNS composition.

4.3.4. **Determination of calorific value**

Samples from urban species were analyzed by means of an adiabatic calorimeter. This test was based on the norm UNE-EN 14918. A minimum number of 16 samples per *Morus alba*, *Platanus hispanica*, *Sophora japonica* and a minimum number of 12 samples per *Phoenix canariensis* and *Phoenix dactilifera* were examined. The theory of operation of the instrument is explained below.

To measure the calorific value of various organic materials collected during field trials a LECO AC500 Automatic Calorimeter was used. The calorific value of each sample was determined by its combustion in a controlled environment at 3000 kPa. The heat released in the process was proportional to the calorific value of the examined substance.

The procedure of trial consisted of the following stages:

1. Sample with weight between 100-1000 mg is prepared.
2. Sample is placed in a combustion vessel. The combustion vessel is located in a water bucket surrounded by a jacket and the sample is ignited. During the analysis the water temperature is measured by an electronic thermometer with a resolution of 1/10.000 of a degree. Some energy exchange may occur between the outside environment and water surrounding the combustion vessel. For this, a continuous monitoring of the buckets and jackets temperatures is held and a correlation to the result is applied.
3. The water temperature is measured by a microprocessor every 6 seconds. An analogue to a digital convertor converts the output into a number stored in the memory.
4. The difference in water temperature between pre-fire and post-fire is processed by a computer. Results are presented as cal/g (LECO, 2009a).
5. Trial is repeated for all samples.

4.3.5. **Determination of total content of carbon, hydrogen and nitrogen**

Samples of examined species were analyzed by means of CHN determinators. This test was based on the norm UNE-EN 15104. A minimum number of 16 samples per *Morus alba*, *Platanus hispanica*, *Sophora japonica* and a minimum number of 12 samples per *Phoenix canariensis* and *Phoenix dactilifera* were examined for each of the elements. The theory of operation of the instrument is explained below:

1. Sample with weight between 100-1000 mg is prepared.
2. The analyze cycle is divided into three phases: purge, combust and analyze.
3. Purge phase: the encapsulated sample is placed in the loading head, sealed and purged of atmospheric gases that entered during sample loading. The ballast volume and gas lines are also purged.
4. Combust phase: sample is dropped into the furnace with temperature 950^{o}C and next flushed with oxygen for rapid and complete combustion. The combustion products pass through an afterburner (850^{o}C) for further oxidation and particulate removal. Next combustion gasses are collected in the ballast (collection vessel).
5. Analyze phase: sample is combusted in the furnace with oxygen flow. Combustion gases are collected in the ballast. Next the homogenous combustion gases in the ballast are purged through the CO_2 and H_2O infrared detectors and the 3cc aliquot loop. After gas equilibration C is measured by the CO_2 detector and H is determined as water vapour in the H_2O detector. The gases in the aliquot loop are transported to the helium carrier flow, swept through hot copper for O removal and NO_X to N_2 change. Next they flow through Lecosorb and Anydrone in

order to remove CO_2 and H_2O. Nitrogen content is determined in a thermal conductivity cell. The results are reported as percentage/ppm or gram (LECO, 2009b).

6. Trial is repeated for all samples.

4.3.6. **Determination of total content of sulphur**

The sulphur content in the examined samples was determined with a Tru-Spec Add-On Module. A minimum number of 16 samples per *Morus alba*, *Platanus hispanica*, *Sophora japonica* and a minimum number of 12 samples per *Phoenix canariensis* and *Phoenix dactilifera* were examined. This was made in the following steps:

1. Sample with weight between 500-1000 mg is prepared and placed in a combustion boat.
2. Sample is combusted in a combustion system with pure oxygen environment and temperature 1350°C.
3. Sample contained in the combustion boat goes through an oxidative reduction process. This results in the release of sulphur from sulphur-bearing compounds. Sulphur oxidizes to SO_2 and is released into the carrier flow as sample gases.
4. Gases from the combustion system flow through an Anhydrone tube in order to remove moisture, through a flow controller and an infrared detection cell.
5. The cell measures the concentration of SO_2 gas present. The instrument automatically converts the value through an equation stored in the software, taking into account sample weight, calibration and known moisture value. The results are reported as percentage/ppm or gram (LECO, 2009c).
6. Trial is repeated for all samples.

All instruments used in the trials were connected to an external PC and use a Windows-based software program in order to control the operations and data management.

4.3.7. **Determination of wood density**

Wood density is expressed as dry mass of wood substance per unit of green volume. The methodology employed involved the determination of dry weight of samples by convection drying with temperature (105±2)°C until the stabilization of weight after 24 hours. The samples were immerged in a beaker with water. The obtained difference equivalent to the volume of displaced water, equals the volume of the sample submerged (Equation 9) (Husch et al., 2003). The mean and standard deviation were calculated for the obtained densities. The material used for this test was a 250ml beaker, distilled water, electronic balance with precision 0.01 g, a holder for the immersion of wood samples and a number of 5 samples for species.

$$D = \frac{Wd}{Vg} \qquad (9)$$

Where
D= wood density (g/cm^3)
Wd= oven-dried weight of wood (g)
Vg= green volume (cm^3)

4.3.8. Determination of percentage of bark

To perform this study several branches of *Morus alba, Platanus hispanica, Sophora japonica* were divided into 4 diameter classes. The diameter classes represent the base of the branch section, midway sections and the upper end section. To determine the percentage of bark, the diameter over bark and the diameter under bark were determined for all analyzed samples within a diameter class (Equation 10). The average percentage of bark was determined within each diameter class. The materials used in this trial were pruning shears, a digital caliper with precision 0.01 mm and a number of 25 samples per species.

$$ba = \frac{dob^2 - dub^2}{dob^2} \cdot 100\% \qquad (10)$$

Where
ba = bark (%)
dob= diameter over bark (mm)
dub= diameter under bark (mm)

5. RESULTS AND DISCUSSION

5.1. ALLOMETRIC PREDICTION OF THE AMOUNT OF RESIDUAL BIOMASS FROM PRUNING

The mean and standard deviation (sd) of quantity of dry biomass obtained per species is shown in the Table 8. It can be noted that there is a high standard deviation for all species. For this, it is verified if better prediction than from the mean can be obtained by indirect methods.

Table 8. Mean values and standard deviation of dry biomass

Species	Mean dry biomass (kg/tree)	sd
Morus alba (street)	31.67	16.88
Morus alba (park)	77.78	29.51
Phoenix canariensis	24.67	7.82
Phoenix dactilifera	36.13	11.37
Platanus hispanica	23.98	15.16
Sophora japonica	18.07	4.25

sd: standard deviation

5.1.1. *Morus alba*

As it was pointed out, the studied *Morus alba* trees were located in two different conditions: street and park. The variable analysis results are presented in Tables 9 and 10.

Table 9. Variable analysis of *Morus alba* trees, street location

Variable	Average	Standard deviation	Standard skewness	Standard kurtosis	Shapiro-Wilks test (P-value)	Maximum	Minimum
Diameter at breast height (cm)	30.12	5.08	0.58	-0.29	0.541	40.70	19.65
Crown diameter (m)	5.45	1.10	0.95	-0.30	0.459	8.10	3.60
Total tree height (m)	8.85	1.49	-1.10	-0.56	0.165	11.10	5.90

Table 10. Variable analysis of *Morus alba* trees, park location

Variable	Average	Standard deviation	Standard skewness	Standard kurtosis	Shapiro-Wilks test (P-value)	Maximum	Minimum
Diameter at breast height (cm)	42.29	12.94	0.92	0.78	0.243	78.90	19.20
Crown diameter (m)	8.62	1.85	1.99	-0.08	0.053	12.50	5.67
Total tree height (m)	9.51	0.78	0.35	-0.71	0.719	11.20	8.10

The variable analysis indicates in this case, that the standardized skewness and kurtosis values are within the range expected for data from a normal distribution. Moreover, all p-values of the Shapiro-Wilks test are bigger than 0.05, what verifies the normality of the data.

Possible dendrometric differences between the two populations were examined by ANOVAs analysis according to diameter at breast height, crown diameter and tree total height (Figure 22).

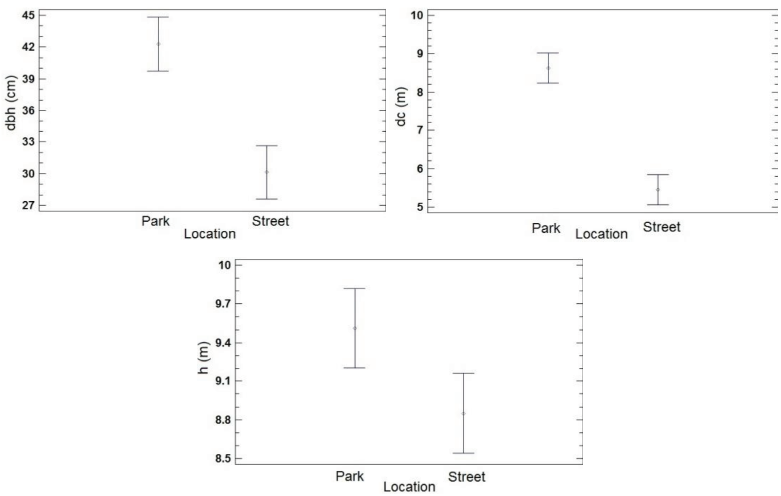


Figure 22. LSD intervals for "Location" factor in *Morus alba* trees at 95% confidence level: dbh: diameter at breast height (cm); dc: crown diameter (m); h: total tree height (m)

According to Figure 22, the two populations of *Morus alba* located in streets and parks were statistically significant different according to all examined dendrometric parameters at the 95.0% confidence level. The park location sample was bigger according to all examined variables. This could influence the biomass analysis.

In this work could be noted that wood formed 100% of total weight of all pruned material before drying, given that the pruning operations were done after the leaves have fallen off. Wood moisture content in wet basis was 46.56% for individuals in park location and 41.42% for individuals in street location. The mean and standard deviation of parameters are presented in Table 11.

Table 11. Mean and standard deviation of dendrometric variables of *Morus alba*

Location, type of pruning	Diameter at breast height (cm)		Crown diameter (m)		Distance from soil to the crown (m)		Total tree height (m)		Dry biomass - wood (kg)	
	mean	sd	mean	sd	mean	Sd	mean	sd	mean	sd
Street location	30.12	5.08	5.45	1.10	2.86	0.40	8.85	1.49	31.67	16.88
Park location	42.29	12.94	8.67	1.92	2.34	0.28	9.51	0.78	77.78	29.51

sd: standard deviation

It is observed that within the sample-tree rage, individuals located in parks are bigger according to all analyzed variables and yield higher quantities of biomass. This sample contained older individuals with wider crowns.

a) Branch form factor and volume functions

Table 12 shows the mean and standard deviation values of the branch form factors obtained for different models. The model that produced a form factor closest to 1 was the paraboloid. This model represented the best fit to characterize the actual form.

Table 12. Mean and standard deviation of form factor of sample branches of *Morus alba*

Model volume	Real volume					
	Huber		Newton		Smalian	
	f	sd f	f	sd f	f	sd f
Cylinder	0.43	0.09	0.43	0.08	0.43	0.08
Paraboloid	0.86	0.18	0.86	0.17	0.86	0.17
Cone	1.29	0.27	1.29	0.26	1.29	0.26
Neiloid	1.73	0.36	1.73	0.35	1.73	0.35

f : mean form factor; sdf : standard deviation of form factor

The variation of the form factor from the base diameter and length of the branches was studied by means of regression models. The coefficients of determination (R^2), standard deviation (sd) and mean absolute error (MAE) are presented in Table 13. The P-values greater than 0.05 (Table 14) indicate, that there is not a statistically significant relationship between the variables at the 95.0% or higher confidence level.

Table 13. Regression model to describe the relationship between f and 2 independent variables do, h in branches of *Morus alba*

Equation	R^2	sd	MAE
f paraboloide = 0.661865 + 0.29047 ·do -0.00144258 ·l	0.157	0.180	0.133

f: form factor; R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error; do: base diameter of a branch (cm); l: length of a branch (cm)

Table 14. Significance of explicative variables for form factor for *Morus alba*

Dependent variable: f paraboloid
Independent variables: do, l

Parameter	Estimation error	Standard error	T statistic	P-Value
Constant	0.661865	0.286492	2.31024	0.0395
do	0.29047	0.194408	1.49412	0.1610
l	-0.00144258	0.00130746	-1.10335	0.2915

f: form factor; do: base diameter of a branch (cm); l: length of a branch (cm)

Table 15 shows the results of adjusting the volume functions for *Morus alba* branches. For each model, were obtained the coefficient of determination, standard deviation and mean absolute error.

Table 15. Branch volume functions for *Morus alba*

Author	Volume function	R^2	sd	MAE
Naslund (modif)*	$V = -591.746 + 507.093 \cdot do^2 - 2.09281 \cdot do^2 \cdot l + 0.0083961 \cdot do \cdot l^2$	0.96	43.63	26.21
Spurr	$V = 33.2341 + 0.308898 \cdot do^2 \cdot l$	0.85	77.89	52.31
Ogaya	$V = -57.6563 + 58.2544 \cdot do^2 + 0.176836 \cdot do^2 \cdot l$	0.87	75.74	50.88
Hoenald-Krenn	$V = -336.144 + 189.778 \cdot do + 82.168 \cdot do^2$	0.85	83.82	58.38

R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error; V: volume of a branch (cm^3); do: base diameter of a branch (cm); l: length of a branch (cm);* best equation validated with independent data

All volume functions presented high coefficients of determination. The ones that presented the best fit were the Spurr and Naslund. Tables 16 and 17 show detailed statistical analysis of the selected volume functions.

Table 16. Significance of explicative variables for Spurr volume function for *Morus alba*

Dependent variable: V
Independent variables: $do^2 \cdot l$

Parameter	Estimate	Standard error	T statistic	P-Value
Constant	33.2341	44.2206	0.751553	0.4657
$do^2 \cdot l$	0.308898	0.0346072	8.92581	0.0000

V: volume of a branch (cm^3); do: base diameter of a branch (cm); l: length of a branch (cm)

Table 17. Significance of explicative variables for Naslund volume function for *Morus alba*

Dependent variable: V
Independent variables: do^2, $do^2 \cdot l$, $do \cdot l^2$

Parameter	Estimate	Standard error	T statistic	P-Value
Constant	-591.746	120.552	-4.90862	0.0027
do^2	507.093	91.3396	5.55173	0.0014
$do^2 \cdot l$	-2.09281	0.459639	-4.55315	0.0039
$do \cdot l^2$	0.0083961	0.00180676	4.64705	0.0035

V: volume of a branch (cm^3); do: base diameter of a branch (cm); l: length of a branch (cm)

In both cases the P-values of all explicative variables were less than 0.05 and there is a statistically significant relationship between the variables at the 95.0% confidence level. Although the Spurr model has a lower coefficient (R^2=0.85), due to lower complexity, it is considered more appropriate for volume calculation.

According to the presented results can be concluded, that the volume functions allow better approximation than the form factor, which has a big variation (sdf).

b) Regression models for biomass prediction

Following regression models were calculated to predict the amount of residual biomass from pruning operations of *Morus alba* from simple measures such as diameter at breast height, crown diameter and total tree height. Tables 18, 19 and 20 show the relationships obtained in street locations where topping technique was applied. Tables 21, 22 and 23 show the results for maintenance pruning, which was carried out in parks.

Table 18. Regression models to describe the relationship between the pruned biomass (B) and only one independent variable for *Morus alba*, street location

Residual biomass versus diameter at breast height (dbh)	
Type of equation	Equation
Linear	$B = -20.1049 + 1.71883 \cdot dbh$
Quadratic	$B = 4.47144 + 0.0291707 \cdot dbh^2$
Residual biomass versus crown diameter (dc)	
Type of equation	Equation
Linear	$B = -46.1278 + 14.2691 \cdot dc$
Quadratic	$B = -6.90073 + 1.24776 \cdot dc^2$
Residual biomass versus total tree height (h)	
Type of equation	Equation
Linear	$B = -19.9197 + 5.82956 \cdot h$
Quadratic	$B = 3.65834 + 0.348094 \cdot h^2$

B: dry biomass (kg)

Table 19. Multiple regression analysis for *Morus alba*, street location

Residual biomass versus diameter at breast height (dbh)			
Type of equation	R^2	sd	MAE
Linear	0.26	14.70	12.24
Quadratic	0.29	14.43	11.96
Residual biomass versus crown diameter (dc)			
Type of equation	R^2	sd	MAE
Linear	0.87	6.06	4.73
Quadratic	0.87	6.12	4.67
Residual biomass versus total tree height (h)			
Type of equation	R^2	sd	MAE
Linear	0.26	14.72	11.64
Quadratic	0.27	14.62	11.52

R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error

The results (Table 19) indicate a high dependence between residual biomass and crown diameter with a coefficient of determination at the level R^2=0.87 in the linear model. Nevertheless, the biomass doesn't show dependence with total height nor with diameter at breast height indicating lack of dependence with tree age.

Table 20. Significance of explicative variables for biomass prediction for *Morus alba*, street location

			Estimate	Standard error	T statistic	P-Value
B versus dbh	Linear model	Constant	-20.1049	16.3798	-1.22742	0.2299
		dbh	1.71883	0.536407	3.20433	0.0034
	Quadratic model	Constant	4.47144	8.37095	0.534162	0.5974
		dbh^2	0.0291707	0.00852106	3.42337	0.0019
B versus dc	Linear model	Constant	-46.1278	5.65645	-8.15491	0.0000
		dc	14.2691	1.01735	14.0257	0.0000
	Quadratic model	Constant	-6.90073	2.99833	-2.30153	0.0290
		dc^2	1.24776	0.0899858	13.8662	0.0000
B versus h	Linear model	Constant	-19.9197	16.4361	-1.21195	0.2357
		h	5.82956	1.83216	3.18179	0.0036
	Quadratic model	Constant	3.65834	8.979379	0.407669	0.6866
		h^2	0.348094	0.106459	3.26973	0.0029

B: dry biomass (kg); dbh: diameter at breast height (cm); dc: crown diameter (m); h: total tree height (m)

It can be seen that there is a statistically significant relationship between the variables at the 95.0% confidence level for all analyzed regression models.

Table 21. Regression models to describe the relationship between the pruned biomass (B) and only one independent variable for *Morus alba*, park location

Residual biomass versus diameter at breast height (dbh)	
Type of equation	Equation
Linear	$B = 36.4781 + 0.968838 \cdot dbh$
Quadratic	$B = 60.7108 + 0.00858288 \cdot dbh^2$
Residual biomass versus crown diameter (dc)	
Type of equation	Equation
Linear	$B = -28.5302 + 12.2848 \cdot dc$
Quadratic	$B = 26.7134 + 0.652531 \cdot dc^2$
Residual biomass versus total tree height (h)	
Type of equation	Equation
Linear	$B = -168.767 + 25.8847 \cdot h$
Quadratic	$B = -46.3957 + 1.35979 \cdot h^2$

B: dry biomass (kg)

Table 22. Multiple regression analysis for *Morus alba*, park location

Residual biomass versus diameter at breast height (dbh)			
Type of equation	R^2	sd	MAE
Linear	0.18	27.13	20.43
Quadratic	0.11	28.14	21.20
Residual biomass versus crown diameter (dc)			
Type of equation	R^2	sd	MAE
Linear	0.59	18.99	14.02
Quadratic	0.60	18.90	14.23
Residual biomass versus total tree height (h)			
Type of equation	R^2	sd	MAE
Linear	0.47	21.68	17.77
Quadratic	0.48	21.55	17.69

R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error

Table 22 also indicates interdependence between residual biomass and crown diameter when annual maintenance pruning is carried out in parks although the coefficient of determination is lower than in topping (R^2=0.60 in the quadratic model). The P-values in the Table 23 are less than 0.05 indicating statistically significant relationship between the variables at the 95.0% confidence level. Only the P-value for the quadratic model of dbh exceeds this value.

Table 23. Significance of explicative variables for biomass prediction for *Morus alba*, park location

			Estimate	Standard error	T statistic	P-Value
B versus dbh	Linear model	Constant	36.4781	17.1883	2.12227	0.0428
		dbh	0.968838	0.389129	2.48976	0.0190
	Quadratic model	Constant	60.7108	10.0169	6.06086	0.0000
		dbh^2	0.00858288	0.00440714	1.9475	0.0616
B versus dc	Linear model	Constant	-28.5302	16.7584	-1.70245	0.0998
		dc	12.2848	1.90039	6.46435	0.0000
	Quadratic model	Constant	26.7134	8.51593	3.13687	0.0040
		dc^2	0.652531	0.100116	6.51775	0.0000
B versus h	Linear model	Constant	-168.767	48.8629	-3.45388	0.0018
		h	25.8847	5.11991	5.05569	0.0000
	Quadratic model	Constant	-46.3957	24.5075	-1.89312	0.0687
		h^2	1.35979	0.265579	5.12008	0.0000

B: dry biomass (kg); dbh: diameter at breast height (cm); dc: crown diameter (m); h: total tree height (m)

In addition, regression models for predicting residual biomass were tested from combinations of variables such us diameter at breast height, crown diameter and total tree height. The best results are shown in the tables below. A high R^2 value (R^2=0.96) was obtained for street location. The combination of these parameters improved the prediction model obtained from only the diameter at breast height. Also a high R^2 value was obtained for park location (R^2=0.88). This result improved the prediction models from one variable (Tables 24, 25, 26 and 27).

Table 24. Regression model to describe the relationship between residual biomass and dendrometric variables for *Morus alba*, street location

Biomass function*	R^2	sd	MAE
$B = 10.288 + 0.0256723 \cdot dbh^2 - 0.182728 \cdot dbh \cdot h - 3.18406 \cdot dc \cdot hc + 1.95276 \cdot h \cdot dc$	0.96	3.61	2.64

B: dry biomass (kg); R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error; dbh: diameter at breast height (cm); dc: crown diameter (m); hc: distance from soil to the crown (m); h: total tree height (m); * best equation validated with independent data

Table 25. Significance of explicative variables for biomass prediction for *Morus alba*, street location

Dependent variable: B
Independent variables: dbh^2, $dbh \cdot h$, $dc \cdot hc$, $h \cdot dc$

Parameter	Estimate	Standard error	T statistic	P-Value
Constant	10.288	7.00902	1.46783	0.1594
dbh^2	0.0256723	0.00478082	5.36984	0.0000
$dbh \cdot h$	-0.182728	0.0289018	-6.32238	0.0000
$dc \cdot hc$	-3.18406	0.795484	-4.00267	0.0008
$h \cdot dc$	1.95276	0.165387	11.8072	0.0000

B: dry biomass (kg); dbh: diameter at breast height (cm); dc: crown diameter (m); hc: distance from soil to the crown (m); h: total tree height (m)

Table 26. Regression model to describe the relationship between biomass and dendrometric variables for *Morus alba*, park location

Biomass function *	R^2	sd	MAE
$B = -1.8355 - 3.04043 \cdot dc \cdot h + 17.7895 \cdot dc \cdot hc + 1.87746 \cdot h^2 - 35.3771 \cdot hc^2$	0.88	11.52	7.68

B: dry biomass (kg); R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error; dc: crown diameter (m); hc: distance from soil to the crown (m); h: total tree height (m); * best equation validated with independent data

Table 27. Significance of regression model for biomass prediction for *Morus alba*, park location

Dependent variable: B
Independent variables: dc·h, dc·hc, h^2, hc^2

Parameter	Estimate	Standard error	T statistic	P-Value
Constant	-1.8355	20.2818	-0.0905	0.9289
dc·h	-3.04043	0.842644	-3.6082	0.0020
dc·hc	17.7895	3.90867	4.5513	0.0002
h^2	1.87746	0.427883	4.38779	0.0004
hc^2	-35.3771	8.43337	-4.1949	0.0005

B: dry biomass (kg); dc: crown diameter (m); hc: distance from soil to the crown (m); h: total tree height (m)

Prediction models for dried pruned biomass calculated from the apparent volume of the crown were also analyzed. As observed in Table 28, there is a good linear relationship between the conical and parabolic volume model and the amount of dry biomass yielded from topping pruning (R^2=0.90). This result could be expected, given that the apparent volume is calculated from combination from crown diameter and height. This indicates a good explanatory power for predicting biomass. A minor difference is observed in the hemispheric volume model (R^2=0.84).

Table 28. Regression model to describe the relationship between biomass and independent variable crown volume for *Morus alba*, street location

Type of model	Equation	R^2	sd	MAE
Conical volume model *	B = 2.65673 + 0.573367 · V cone	0.90	5.70	4.32
Parabolic volume model*	B = 2.65673 + 0.382245·V paraboloid	0.90	5.70	4.32
Hemispheric volume model	B= 6.67744 + 0.524836·V hemisphere	0.84	6.79	5.04

B: dry biomass (kg); R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error; * best equation validated with independent data

Since the conical and parabolic volume model are proportional and present the same coefficient of determination, the model with lower standard error, estimate and T statistic value is described below (Table 29).

Table 29. Significance of regression model for biomass prediction from crown volume for *Morus alba*, street location

Dependent variable: B
Independent variable: V paraboloid

Parameter	Estimate	Standard error	T statistic	P-Value
Constant	2.65673	2.38574	1.11359	0.2770
V paraboloid	0.382245	0.0263155	14.5254	0.0000

B: dry biomass (kg)

Table 30 shows that there is a lower relationship between the conical and parabolic volume model and the amount of dry biomass yielded from annual maintenance pruning (R^2=0.59).

Table 30. Regression model to describe the relationship between biomass and independent variable crown volume for *Morus alba*, park location

Type of model	Equation	R^2	sd	MAE
Conical volume model	B = 37.413 + 0.265421 · Vcone	0.59	19.03	14.42
Parabolic volume model	B = 37.413 + 0.176947 · Vparaboloid	0.59	19.03	14.42
Hemispheric volume model	B= 45.108 + 0.168542 · Vhemisphere	0.59	19.15	14.58

B: dry biomass (kg): R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error

The model with the lowest standard error, estimate and T statistic values is described below (Table 31).

Table 31. Significance of regression model for biomass prediction from crown volume for *Morus alba*, park location

Dependent variable: B				
Independent variables: V paraboloid				
Parameter	Estimate	Standard error	T statistic	P-Value
Constant	37.413	7.12473	5.25115	0.0000
V paraboloid	0.176947	0.0274815	6.43878	0.0000

B: dry biomass (kg)

The park location sample was bigger according to all dendrometric variables and yielded higher quantities of biomass. Reasons exist to believe that the quantity of residual biomass depends not only on tree dimensions but is also strongly correlated with type of pruning practice applied. Where, the type of pruning practice applied, depends on the location of the tree and all functions and limits related to it (Michau, 1987, Gil-Albert, 201, Drenou, 2006).

A high relationship between crown diameter (R^2=0.87) as well as apparent crown volume (R^2=0.90) and dry biomass were observed for topping type of pruning practice and street location. This is explained by the characteristics of the pruning operation, where practically a major part of the canopy is being removed from the tree, leaving mostly branch stubs (Michau, 1987). This results in significant reduction of crown volume.

In case of annual maintenance type of pruning, there is no clear interdependence between lonely parameters and quantity of dry biomass. The best result is found between crown diameter and yielded residual biomass in quadratic model (R^2=0.60). For this, a combination of parameters was tested, what led to an improved result (R^2=0.88). This may be explained by the characteristics of the pruning practice, were both tree height and crown diameters are reduced in a rather equal way (Michau, 1987). Annual maintenance type of pruning leads to the elimination of annual branches. Therefore, the total tree height and crown diameter are affected, but not as strongly as in topping type of pruning. It is important to mention, that the diameter at breast height does not present high interdependence with the obtained biomass (R^2=0.18). This means that the incensement of age, and therefore quantity of branched in older trees does not influence the quantity of biomass. This may be caused due to the high vigour of young trees. This fact shows a clear difference with the trees from forest systems.

5.1.2. ***Platanus hispanica***

The variable analysis results are presented in Table 32. The analysis indicates that the standardized skewness and kurtosis values are within the range expected for data from a normal distribution and P-values of the Shapiro Wilks test are higher than 0.05. The tree-sample includes individuals with small to large canopies and heights. Compared sample trees of *Platanus hispanica* are characterized with mean diameter at breast height 23.56 cm, mean crown diameter 8.44 m, mean distance from soil to the crown 3.76 m and mean total height 11.57 m. 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 biomass for all sample trees were 23.98 kg and 15.16 kg respectively.

Table 32. Variable analysis of *Platanus hispanica* trees

Variable	Average	Standard deviation	Standard skewness	Standard kurtosis	Shapiro Wilks test (P-value)	Maximum	Minimum
Diameter at breast height (cm)	23.56	7.92	1.12	0.56	0.303	45.50	11.20
Crown diameter (m)	8.44	2.41	0.37	-0.86	0.778	13.30	4.10
Total tree height (m)	11.57	2.38	0.55	0.26	0.795	17.00	6.40

a) Branch form factor and volume functions

Table 33 shows the results of mean and standard deviation values of the branch form factors obtained from different models for *Platanus hispanica*. The model that produced a form factor closest to 1 was the cylinder. This model represented the best fit to characterize the actual volume.

Table 33. Mean and standard deviation of form factor of sample branches of *Platanus hispanica*

	Real volume					
Model volume	Huber		Newton		Smalian	
	f	sd f	f	sd f	f	sd f
Cylinder	0.72	0.11	0.72	0.11	0.71	0.11
Paraboloid	1.45	0.23	1.44	0.23	1.43	0.22
Cone	2.18	0.35	2.17	0.34	2.14	0.34
Neiloid	2.91	0.47	2.89	0.46	2.86	0.45

f : mean form factor; sdf : standard deviation of form factor

The variation of the form factor from the base diameter and length of the branches was studied by means of regression models. The coefficients of determination, standard deviation and mean absolute error are presented in Table 34.

Table 34. Regression model to describe the relationship between f and 2 independent variables do, h in branches of *Platanus hispanica*

Equation	R^2	sd	MAE
$f = 0.878299 + 0.0996161 \cdot do - 0.00478805 \cdot l$	0.50	0.08	0.07

f: form factor; R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error; do: base diameter of a branch (cm); l: length of a branch (cm)

The low values of R^2 can indicate that the model for form factor calculation explains poorly its variability. Therefore, if this technique is used to calculate the volume, the mean must be used.

Table 35. Significance of explicative variables for form factor for *Platanus hispanica*

Dependent variable: f cylinder
Independent variables: do, l

Parameter	Estimate	Standard error	T statistic	P-Value
Constant	0.878299	0.0878208	10.001	0.0000
do	0.0996161	0.0307073	3.24405	0.0059
l	-0.00478805	0.00141765	3.37745	0.0045

f: form factor; do: base diameter of a branch (cm); l: length of a branch (cm)

On the other hand, Table 36 shows the results of adjusting the volume functions for *Platanus hispanica* branches. For each model, were obtained the coefficient of determination, standard deviation and mean absolute error.

Table 36. Branch volume functions for *Platanus hispanica*

Author	Volume function	R^2	sd	MAE
Naslund (modif)	$V = -0.96235 + 3.02575 \cdot do^2 + 0.681096 \cdot do^2 \cdot l - 0.00375207 \cdot do \cdot l^2$	0.99	21.63	13.50
Spurr *	$V = -11.2731 + 0.620237 \cdot do^2 \cdot l$	0.99	27.14	19.13
Ogaya	$V = -21.0495 + 15.4334 \cdot do^2 + 0.457927 \cdot do^2 \cdot l$	0.99	22.39	15.74
Hoenald-Krenn	$V = 56.5386 - 106.076 \cdot do + 80.7595 \cdot do^2$	0.97	36.95	25.20

R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error; V: volume of a branch (cm^3); do: base diameter of a branch (cm); l: length of a branch (cm); * best equation validated with independent data

The coefficients of determination (R^2) for all the analyzed models were high. Although Naslund equation had the highest R^2 value, all its explicative variables were not significant. The volume function that presented the lowest P-values in its variables was Spurr. Table 37 presents a detailed statistical analysis of the selected volume functions.

Table 37. Significance of explicative variables for Spurr volume function for *Platanus hispanica* branches

Dependent variable: V
Independent variables: $do^2 \cdot l$

Parameter	Estimate	Standard error	T statistic	P-Value
Constant	-11.2731	11.6888	-0.964431	0.3576
$do^2 \cdot l$	0.620237	0.0201921	30.7167	0.0000

V: volume of a branch (cm^3); do: base diameter of a branch (cm); l: length of a branch (cm)

The P-value is less than 0.05. There is a statistically significant relationship between the variables at the 95.0% confidence level.

b) Regression models for biomass prediction

Following regression models were calculated to predict the amount of residual biomass from crown raising pruning operations of *Platanus hispanica* from simple measures such as diameter at breast height, crown diameter and total tree height (Table 38 and 39).

Table 38. Regression models to describe the relationship between the pruned biomass (B) and only one independent variable for *Platanus hispanica*

Residual biomass versus diameter at breast height (dbh)	
Type of equation	Equation
Linear	$B = -16{,}4074 + 1{,}71395 \cdot dbh$
Quadratic	$B = 2{,}83173 + 0{,}0343369 \cdot dbh^2$
Residual biomass versus crown diameter (dc)	
Type of equation	Equation
Linear	$B = -18{,}6037 + 5{,}04282 \cdot dc$
Quadratic	$B = 1{,}03702 + 0{,}298084 \cdot dc^2$
Residual biomass versus total tree height (h)	
Type of equation	Equation
Linear	$B = -31{,}7936 + 4{,}81816 \cdot h$
Quadratic	$B = -5{,}1046 + 0{,}208479 \cdot h^2$

B: dry biomass (kg)

Table 39. Multiple regression analysis for *Platanus hispanica*

Residual biomass versus diameter at breast height (dbh)			
Type of equation	R^2	sd	MAE
Linear	0.80	6.88	5.11
Quadratic	0.87	5.55	4.30
Residual biomass versus crown diameter (dc)			
Type of equation	R^2	sd	MAE
Linear	0.64	9.17	6.43
Quadratic	0.68	8.60	6.02
Residual biomass versus total tree height (h)			
Type of equation	R^2	sd	MAE
Linear	0.57	10.06	7.20
Quadratic	0.61	9.55	7.18

R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error

The results in Table 39 indicate, that there is a high interdependence between residual biomass and diameter at breast height with a coefficient of determination at the level R^2 =0.87 in the quadratic model. This indicates a good explanatory power for predicting biomass. There is also an interdependence between the residual biomass and crown diameter at the level R^2 =0.68 in the quadratic model.

Table 40. Significance of explicative variables for biomass prediction of *Platanus hispanica*

			Estimate	Standard error	T statistic	P-Value
B versus dbh	Linear model	Constant	-16.4074	4.00646	-4.09525	0.0003
		dbh	1.71395	0.16142	10.618	0.0000
	Quadratic model	Constant	2.83173	1.84457	1.53517	0.1360
		dbh^2	0.0343369	0.00250148	13.7266	0.0000
B versus dc	Linear model	Constant	-18.6037	6.17453	-3.01298	0.0054
		dc	5.04282	0.703727	7.16588	0.0000
	Quadratic model	Constant	1.03702	3.30936	0.31336	0.7563
		dc^2	0.298084	0.0378327	7.879	0.0000
B versus h	Linear model	Constant	-31.7936	9.24295	-3.43977	0.0018
		h	4.81816	0.782486	6.1575	0.0000
	Quadratic model	Constant	-5.1046	4.6728	-1.09241	0.2840
		h^2	0.208479	0.0310664	6.71078	0.0000

B: dry biomass (kg); dbh: diameter at breast height (cm); dc: crown diameter (m); h: total tree height (m)

The P-values in Table 40 are less than 0.05. This indicates that there is a statistically significant relationship between the variables at the 95.0% confidence level.

In addition, regression models for predicting residual biomass were tested from combinations of variables such us diameter at breast height, crown diameter and total tree height. The best result is shown in the Table 41 and 42. Although a high R^2 value (R= 0.93) was obtained, the combination of these parameters did not improve significantly the prediction model obtained from only the diameter at breast height.

Table 41. Regression model to describe the relationship between biomass and dendrometric variables for *Platanus hispanica*

Equation*	R^2	sd	MAE
$B = 3.3003 + 0.270102 \cdot dc \cdot dbh - 0.500268 \cdot dc^2$	0.93	4.52	3.32

R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error; dbh: diameter at breast height (cm); dc: crown diameter (m); * best equation validated with independent data

Table 42. Significance of explicative variables for biomass prediction for *Platanus hispanica*

Dependent variable: B
Independent variables: dc^2 , $dbh \cdot dc$

Parameter	Estimate	Standard error	T statistic	P-Value
Constant	3.3003	1.99139	1.65729	0.1131
dc^2	-0.500268	0.110639	-4.52161	0.0002
$dbh \cdot dc$	0.270102	0.0352703	7.65807	0.0000

B: dry biomass (kg); dbh: diameter at breast height (cm); dc: crown diameter (m)

Below are presented the prediction models calculated from the apparent volume of the crown. As observed in Table 43 there is a good linear relationship between the conical and parabolic volume model and the amount of dry biomass yielded from pruning (R^2=0.78). A minor difference is observed in the hemispheric volume model (R^2=0.71).

Table 43. Regression model to describe the relationship between biomass and independent variable crown volume for *Platanus hispanica*

Type of model	Equation	R^2	sd	MAE
Conical volume model *	B = 6.10934 + 0.0992547· Vcone	0.78	7.62	5.30
Parabolic volume model	B = 6.10934 + 0.0661698· Vparaboloid	0.78	7.62	5.30
Hemispheric volume model	B = 7.8498 + 0.0824432· Vhemisphere	0.71	8.29	6.17

B: dry biomass (kg); R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error; * best equation validated with independent data

The model with the lowest standard error, estimate and T statistic values is described below (Table 44).

Table 44. Significance of explicative variables for residual biomass prediction for *Platanus hispanica*

Dependent variable: B
Independent variables: V paraboloid

Parameter	Estimate	Standard error	T statistic	P-Value
Constant	6.10934	2.5908	2.35809	0.0272
V paraboloid	0.0661698	0.00725681	9.11831	0.0000

B: dry biomass (kg)

The high interdependence between the quantity of pruned biomass and diameter at breast height (R^2 =0.87) is probably the result of the pruning practice applied. The crown raising type of pruning is highly dependent from the age of the tree as it is used to give a tree a particular form. It is important to mention that crown raising is introduced in young trees, that have very thin branches (Michau, 1987). When the tree is older, the lower branches are thicker, therefore probably the residual biomass obtained by this pruning type in bigger, as shown by the positive coefficient of the dhb in the Table 39.

The relationship between biomass and crown diameter (R^2 =0.68) can be explained by the fact that crown raising is based on removing the lower braches which are in many cases the oldest and widest ones. Nevertheless, it is important to point that the lower branches do not receive as much light as in the top when the crown is fully developed and therefore these branches will grow more slowly, leading to lack of pruning after a certain age of the tree or to less frequency.

5.1.3. ***Sophora japonica***

The variable analysis results are presented in Table 45. The sample includes rather young trees. It can be observed that the variables follow a normal distribution (Shapiro-Wilks test P-value > 0.05).

Table 45. Variable analysis for *Sophora japonica* trees

Variable	Average	Standard deviation	Standard skewness	Standard kurtosis	Shapiro-Wilks test (P-value)	Maximum	Minimum
Diameter at breast height (cm)	17.80	2.39	1.00	-0.45	0.317	23.00	13.80
Crown diameter (m)	6.95	0.98	1.72	0.98	0.225	9.75	5.35
Total tree height (m)	10.22	1.10	-0.09	0.04	0.684	12.40	7.60

Sample trees of *Sophora japonica* are characterized with mean diameter at breast height 17.80 cm, mean crown diameter 6.95 m, mean distance from soil to the crown 3.53 m and mean total height 10.2 2m. Wood formed 59.97% of total weight of all pruned material before drying while the rest 40.03% belonged to leaves. Wood moisture content was 44.88% in wet basis. The mean and standard deviation of residual biomass for all sample trees were 18.07 kg and 4.25 kg, respectively.

a) Branch form factor and volume functions

Table 46 shows the results of mean and standard deviation values of the branch form factors obtained for different models. The model that produced a form factor closest to 1 was the paraboloid. This model represented the best fit to characterize the actual shape.

Table 46. Mean and standard deviation of form factor of sample branches of *Sophora japonica*

	Real volume					
Model volume	Huber		Newton		Smalian	
	f	sd f	f	sd f	f	sd f
Cylinder	0.58	0.10	0.58	0.09	0.57	0.09
Paraboloid	1.16	0.20	1.16	0.19	1.15	0.18
Cone	1.74	0.30	1.74	0.29	1.72	0.27
Neiloid	2.32	0.40	2.32	0.38	2.30	0.36

f: mean form factor; sdf :standard deviation of form factor

The variation of the form factor from the base diameter and length of the branches was studied by means of regression models. The coefficients of determination, standard deviation and mean absolute error are presented in Table 47.

Table 47. Regression model to describe the relationship between f and 2 independent variables do, h in branches of *Sophora japonica*

Form factor function	R^2	sd	MAE
$f = 0.908292 - 0.199766 \cdot do - 0.000713573 \cdot l$	0.20	0.09	0.07

f: form factor; R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error; do: base diameter of a branch (cm); l: length of a branch (cm)

P-values are greater than 0.05 can indicate that the form factor is not dependent of these variables (Table 48). There is not a statistically significant relationship between the variables at the 95.0% or higher confidence level. Therefore, the mean must be used for volume calculation.

Table 48. Significance of explicative variables for form factor for *Sophora japonica*

Dependent variable: f cylinder
Independent variables: do, l

Parameter	Estimate	Standard error	T statistic	P-Value
Constant	0.908292	0.191433	4.74471	0.0004
do	-0.199766	0.131484	-1.51932	0.1526
l	-0.000713573	0.00110003	-0.648684	0.5278

f: form factor; do: base diameter of a branch (cm); l: length of a branch (cm)

Table 49 shows the results of adjusting the volume functions for *Sophora japonica* branches. For each model, were obtained the coefficient of determination, standard deviation and mean absolute error.

Table 49. Branch volume functions for *Sophora japonica*

Author	Volume function	R^2	sd	MAE
Naslund (modif)	$V = -51.7828 + 149.11 \cdot do^2 - 1.16356 \cdot do^2 \cdot l + 0.00673976 \cdot do \cdot l^2$	0.86	12.03	8.31
Spurr *	$V = 23.6538 + 0.313124 \cdot do^2 \cdot l$	0.71	5.12	12.27
Ogaya	$V = 12.7026 + 9.5878 \cdot do^2 + 0.305009 \cdot do^2 \cdot l$	0.80	13.80	10.48
Hoenald-Krenn	$V = -15.6948 + 44.1069 \cdot do + 35.16 \cdot do^2$	0.68	17.68	13.21

R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error; V: volume of a branch (cm^3); do: base diameter of a branch (cm); l: length of a branch (cm); * best equation validated with independent data

The coefficients of determination for all the analyzed models were high. The volume function that presented the lowest P-values was the Spurr. Table 50 presents a detailed statistical analysis of the selected volume functions.

Table 50. Significance of explicative variables for Spurr volume function for *Sophora japonica* branches

Dependent variable: V
Independent variables: $do^2 \cdot l$

Parameter	Estimate	Standard error	T statistic	P-Value
Constant	23.6538	12.9521	1.82625	0.1011
$do^2 \cdot l$	0.313124	0.0665157	4.70752	0.0011

V: volume of a branch (cm^3); do: base diameter of a branch (cm); l: length of a branch (cm)

The P-value is less than 0.05, for that there is a statistically significant relationship between the variables at the 95.0% confidence level.

b) Regression models for biomass prediction

Regression models were calculated to predict the amount of residual biomass from topping operations of *Sophora japonica* from simple measures such as diameter at breast height, crown diameter and total tree height (Table 51).

Table 51. Regression models to describe the relationship between the pruned biomass (B) and only one independent variable for *Sophora japonica*

Residual biomass versus diameter at breast height (dbh)	
Type of equation	Equation
Linear	$B = -6.01363 + 1.35314 \cdot dbh$
Quadratic	$B = 6.39409 + 0.036227 \cdot dbh^2$
Residual biomass versus crown diameter (dc)	
Type of equation	Equation
Linear	$B = 1.83398 + 2.33671 \cdot dc$
Quadratic	$B = 10.1679 + 0.160592 \cdot dc^2$
Residual biomass versus total tree height (h)	
Type of equation	Equation
Linear	$B = 2.53502 + 1.51976 \cdot h$
Quadratic	$B = 9.99374 + 0.0764211 \cdot h^2$

B: dry biomass (kg)

Table 52. Multiple regression analysis for *Sophora japonica*

Residual biomass versus diameter at breast height (dbh)			
Type of equation	R^2	sd	MAE
Linear	0.57	2.80	2.28
Quadratic	0.55	2.87	2.33
Residual biomass versus crown diameter (dc)			
Type of equation	R^2	sd	MAE
Linear	0.29	3.64	2.86
Quadratic	0.29	3.63	2.81
Residual biomass versus total tree height (h)			
Type of equation	R^2	sd	MAE
Linear	0.15	3.97	3.04
Quadratic	0.16	3.94	3.04

R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error

The results in the Table 52 indicate that there is an interdependence between residual biomass and diameter at breast height with a coefficient of determination at the level R^2=0.57 in the linear model.

Table 53. Significance of explicative variables for biomass prediction of *Sophora japonica*

			Estimate	Standard error	T statistic	P-Value
B versus dbh	Linear model	Constant	-6.01363	3.91471	-1.53616	0.1357
		dbh	1.35314	0.218015	6.20665	0.0000
	Quadratic model	Constant	6.39409	2.02861	3.15196	0.0038
		dbh^2	0.036227	0.00607795	5.9604	0.0000
B versus dc	Linear model	Constant	1.83398	4.84315	0.378674	0.7078
		dc	2.33671	0.690234	3.3854	0.0021
	Quadratic model	Constant	10.1679	2.4023	4.23259	0.0002
		dc^2	0.160592	0.046898	3.42428	0.0019
B versus h	Linear model	Constant	2.53502	6.83493	0.370891	0.7135
		h	1.51976	0.664682	2.28644	0.0300
	Quadratic model	Constant	9.99374	3.49134	2.86243	0.0079
		h^2	0.0764211	0.0323063	2.36552	0.0252

B: dry biomass (kg); dbh: diameter at breast height (cm); dc: crown diameter (m); h: total tree height (m)

The P-values in the Table 53 are less than 0.05. This indicates that there is a statistically significant relationship between the variables at the 95.0% confidence level.

In addition, to improve the regression models for predicting residual biomass, combinations of variables such us diameter at breast height, crown diameter and total tree height were tested. The best result is shown in Table 54 and 55. A high R^2 value (R=0.76) was obtained, so the combination of these parameters improved significantly the prediction model obtained from only the diameter at breast height.

Table 54. Regression model to describe the relationship between B and dendrometic variables for *Sophora japonica*

Equation *	R^2	sd	MAE
$B = 11.3625 - 0.871214 \cdot hc \cdot h + 0.213012 \cdot hc \cdot dbh + 0.168353 \cdot h^2 + 0.0274955 \cdot hc \cdot h \cdot dc$	0.76	2.08	1.52

B: dry biomass (kg); R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error; dbh: diameter at breast height (cm); hc: distance from soil to the crown (m); h: total tree height (m); * best equation validated with independent data

Table 55. Significance of explicative variables for biomass prediction for *Sophora japonica*

Dependent variable: B
Independent variables: $hc \cdot h$, $hc \cdot dbh$, h^2, $hc \cdot h \cdot dc$

Parameter	Estimate	Standard error	T statistic	P-Value
Constant	11.3625	3.61503	3.14312	0.0059
$hc \cdot h$	-0.871214	0.135502	-6.42953	0.0000
$hc \cdot dbh$	0.213012	0.0801992	2.65603	0.0166
h^2	0.168353	0.0366845	4.58923	0.0003
$hc \cdot h \cdot dc$	0.0274955	0.0126113	2.18023	0.0436

B: dry biomass (kg); dbh: diameter at breast height (cm); dc: crown diameter (m); hc: distance from soil to the crown (m); h: total tree height (m)

Next, prediction models calculated from the apparent volume of the crown were analyzed. As observed in Table 56, there is a low relationship between the conical and parabolic volume model and the amount of dry biomass obtained from pruning (R^2=0.37). This fact could be due to the hard pruning practiced in the crown. This can be seen in trees of figures 9 and 10, where only the main branches were not pruned. The hard pruning influences the crown volume each year. Therefore the prediction equations did not involve good statistical parameters. A minor difference is observed in the hemispheric volume model (R^2=0.29). Conical and parabolic volume model present the same coefficient of determination because they are proportional (Table 56). P-values are less than 0.05, therefore there is a statistically significant relationship between the variables at the 95.0% confidence level (Table 57).

Table 56. Regression model to describe the relationship between biomass and independent variable crown volume for *Sophora japonica*

Type of model	Equation	R^2	sd	MAE
Conical volume model	B = 11.0513 + 0.0805709 · V cone	0.37	3.41	2.64
Parabolic volume model	B = 11.0513 + 0.0537139 · V paraboloid	0.37	3.41	2.64
Hemispheric volume model	B = 13.0227 + 0.0542687 · V hemisphere	0.29	3.63	2.78

B: dry biomass (kg); R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error

Table 57. Significance of explicative variables for biomass prediction for *Sophora japonica*

Dependent variable: B
Independent variables: V paraboloid

Parameter	Estimate	Standard error	T statistic	P-Value
Constant	11.0513	1.81309	6.0953	0.0000
V paraboloid	0.0537139	0.0130225	4.12471	0.0003

B: dry biomass (kg)

An interdependence between diameter at breast height and dry residual biomass (R^2 =0.57) was observed for topping type of pruning practice. This indicates that the species produces more biomass with age. This may be caused, due to the fact that older trees have more and thicker branches in the crown. The best prediction model was given with the combination of several dendrometric variables, such as total height, crown height, crown diameter and diameter at breast height (R^2=0.76).

5.1.4. *Phoenix canariensis*

The variable analysis results are presented in Table 58. It can be observed that the values are within the range expected for data from a normal distribution.

Table 58. Variable analysis of *Phoenix canariensis* trees

Variable	Average	Standard deviation	Standard skewness	Standard kurtosis	Shapiro-Wilks test (P-value)	Maximum	Minimum
Diameter at breast height (cm)	68.23	8.66	1.95	1.40	0.053	90.80	54.50
Crown diameter (m)	7.00	0.70	-0.93	1.40	0.345	8.40	5.00
Total tree height (m)	7.78	1.40	-1.74	-0.03	0.071	9.70	4.60

The *Phoenix canariensis* sampled trees are characterized with mean diameter at breast height 68.23 cm, mean crown diameter 7.00 m, mean distance from soil to the crown 3.58 m and mean total height 7.78 m. A number of 962 palm fronds were examined. The palm fronds are characterized with mean length 3.86 m and mean weight of green frond 3.35 kg. The average number of cut fronds per tree was 32.06. Wood moisture content was measured in 3 parts of the frond (lower, middle and upper section). Mean wood moisture content was 74.82% in wet basis. The mean and standard deviation of biomass for all sample trees were 24.67 kg and 7.82 kg respectively.

a) Regression models for biomass prediction

Several regression models were calculated to predict the amount of residual biomass from annual pruning operations of *Phoenix canariensis* from simple measures such as diameter at breast height, crown diameter and total tree height. The R^2 in the Table 59 indicate that there is no interdependence between residual biomass and any lonely dendrometric variable. Nevertheless the R^2 reaches 0.88 when several variables are examined together. Tables 59, 60 and 61 show the results for annual pruning of this species.

Table 59. Regression models to describe the relationship between the pruned biomass (B) and only one independent variable for *Phoenix canariensis*

Residual biomass versus diameter at breast height (dbh)	
Type of equation	Equation
Linear	$B = 35.0669 – 0.119591 \cdot dbh$
Quadratic	$B = 31.8727 – 0.00105024 \cdot dbh^2$
Residual biomass versus crown diameter (dc)	
Type of equation	Equation
Linear	$B = -1.50216 + 4.05595 \cdot dc$
Quadratic	$B = 13.0844 + 0.278992 \cdot dc^2$
Residual biomass versus total tree height (h)	
Type of equation	Equation
Linear	$B = 1.6853 + 3.23786 \cdot h$
Quadratic	$B = 12.8137 + 0.225234 \cdot h^2$

B: dry biomass (kg)

Table 60. Multiple regression analysis for *Phoenix canariensis*

Residual biomass versus diameter at breast height (dbh)			
Type of equation	R^2	sd	MAE
Linear	0.01	7.90	5.95
Quadratic	0.02	7.86	5.92
Residual biomass versus crown diameter (dc)			
Type of equation	R^2	sd	MAE
Linear	0.13	7.41	5.75
Quadratic	0.12	7.47	5.83
Residual biomass versus total tree height (h)			
Type of equation	R^2	sd	MAE
Linear	0.33	6.49	5.03
Quadratic	0.34	6.44	4.96

R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error

Table 61 shows that some P-values are greater or 0.05. These variables are not statistically significant at the 95.0% confidence level.

Table 61. Significance of explicative variables for biomass prediction of *Phoenix canariensis*

			Estimate	Standard error	T statistic	P-Value
B versus dbh	Linear model	Constant	35.0669	11.8485	2.95962	0.0063
		dbh	-0.119591	0.172315	-0.694025	0.4936
	Quadratic model	Constant	31.8727	5.80661	5.48903	0.0000
		dbh^2	-0.00105024	0.0011887	-0.883523	0.3848
B versus dc	Linear model	Constant	-1.50216	13.9265	-0.107864	0.9149
		dc	4.05595	1.97852	2.04999	0.0502
	Quadratic model	Constant	13.0844	7.30539	1.79105	0.0845
		dc^2	0.278992	0.144762	1.92724	0.0645
B versus h	Linear model	Constant	1.6853	6.93872	0.242883	0.8099
		h	3.23786	0.877181	3.69121	0.0010
	Quadratic model	Constant	12.8137	3.90688	3.27979	0.0029
		h^2	0.225234	0.0594392	3.78933	0.0008

B: dry biomass (kg); dbh: diameter at breast height (cm); dc: crown diameter (m); h: total tree height (m)

In addition, regression models for predicting residual biomass were tested from combinations of variables such as diameter at breast height, crown diameter and total tree height. The best result is shown in the tables below. A high R^2 value (R^2=0.88) was obtained. There is a statistically significant relationship between the variables at the 95.0% confidence level. The combination of these parameters improved the prediction models obtained from only one variable (Tables 62 and 63).

Table 62. Regression model to describe the relationship between residual biomass and dendrometric variables for *Phoenix canariensis*

Equation *	R^2	sd	MAE
$B = -483.752 + 145.266 \cdot dc - 36.1174 \cdot h + 56.9057 \cdot hc - 0.395022 \cdot dbh \cdot dc + 0.840297 \cdot dbh \cdot h - 0.896813 \cdot dbh \cdot hc - 4.74705 dc^2 - 6.50947 \cdot dc \cdot h + 8.45532 \cdot h \cdot hc - 8.75568 \cdot hc^2$	0.88	4.09	2.04

B: dry biomass (kg); R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error; dbh: diameter at breast height (cm); dc: crown diameter (m); hc: distance from soil to the crown (m); h: total tree height (m); * best equation validated with independent data

Table 63. Significance of explicative variables for biomass prediction for *Phoenix canariensis*

Dependent variable: B
Independent varable: dc, h, hc, dbh · hc, dbh · h , dbh · hc, dc^2, dc · h, h · hc, hc^2

Parameter	Estimate	Standard error	T statistic	P-Value
Constant	-483.752	103.32	-4.68209	0.0004
dc	145.266	29.943	4.85142	0.0003
h	-36.1174	9.53202	-3.78906	0.0023
hc	56.9057	12.9054	4.40945	0.0007
dbh · hc	-0.395022	0.0931535	-4.24055	0.0010
dbh · h	0.840297	0.169924	4.94513	0.0003
dbh · hc	-0.896813	0.19612	-4.57278	0.0005
dc^2	-4.74705	1.39458	-3.40392	0.0047
dc · h	-6.50947	1.33858	-4.86298	0.0003
h · hc	8.45532	2.22375	3.80227	0.0022
hc^2	-8.75568	2.39799	-3.65126	0.0029

B: dry biomass (kg); dbh: diameter at breast height (cm); dc: crown diameter (m); hc: distance from soil to the crown (m); h: total tree height (m)

Prediction models calculated from the apparent volume of the crown were also analyzed. As observed in Table 64, there is no relationship between the crown volume model and the amount of dry biomass obtained from pruning.

Table 64. Regression model to describe the relationship between biomass and independent variable crown volume for *Phoenix canariensis*

Type of model	Equation	R^2	sd	MAE
Conical volume model	B = 16.4062 + 0.195602 · V cone	0.16	7.30	5.86
Parabolic volume model	B = 16.4062 + 0.130401 · V paraboloid	0.16	7.30	5.86
Hemispheric volume model	B = 18.1107 + 0.0950477 · V hemisphere	0.10	7.53	5.88

B: dry biomass (kg); R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error

The model with the lowest standard error, estimate and T statistic values is described below (Table 65)

Table 65. Significance of explicative variables for biomass prediction for *Phoenix canariensis*

Dependent variable: B Independent variable: V paraboloid				
Parameter	Estimate	Standard error	T statistic	P-Value
Constant	16.4062	4.82243	3.40207	0.0021
V paraboloid	0.130401	0.0574664	2.26917	0.0315

B: dry biomass (kg)

5.1.5. ***Phoenix dactilifera***

Table 66 shows the variable analysis which indicates that the standardized skewness and kurtosis values are within the range expected for data from a normal distribution.

Table 66. Variable analysis of *Phoenix dactilifera* trees

Variable	Average	Standard deviation	Standard skewness	Standard kurtosis	Shapiro-Wilks test (P-value)	Maximum	Minimum
Diameter at breast height (cm)	43.96	6.79	0.94	-0.34	0.202	60.00	33.25
Crown diameter (m)	7.49	1.24	-0.42	1.70	0.053	10.32	4.41
Total tree height (m)	9.97	3.32	1.27	-0.25	0.267	17.30	4.60

Analysed sample trees of *Phoenix dactilifera* are characterized with mean diameter at breast height 43.96 cm, mean crown diameter 7.49 m, mean distance from soil to the crown 5.69 m and mean total height 9.97 m. A number of 1309 palm fronds were examined. The palm fronds are characterized with mean length 3.83m and mean weight of green frond 2.68 kg. The average number of cut fronds per tree was 46.75. Wood moisture content was measured in 3 parts of the frond (lower, middle and upper section). Mean wood moisture content was 71.03% in wet basis. The mean and standard deviation of biomass for all sample trees were 36.13 kg and 11.37 kg respectively.

a) Regression models for biomass prediction

Following regression models were calculated to predict the amount of residual biomass from annual pruning operations of *Phoenix dactilifera* from simple measures such as diameter at breast height, crown diameter and total tree height (Table 67).

Table 67. Regression models to describe the relationship between the pruned biomass (B) and only one independent variable for *Phoenix dactilifera*

Residual biomass versus diameter at breast height (dbh)	
Type of equation	Equation
Linear	$B = 36.6599 - 0.011933 \cdot dbh$
Quadratic	$B = 36,7375 - 0,000304493 \cdot dbh^2$
Residual biomass versus crown diameter (dc)	
Type of equation	Equation
Linear	$B = 17.6568 + 2.46572 \cdot dc$
Quadratic	$B = 27.0116 + 0.15821 \cdot dc^2$
Resisual biomass versus total tree height (h)	
Type of equation	Equation
Linear	$B = 30.6891 + 0.545904 \cdot h$
Quadratic	$B = 32.9225 + 0.0291616 \cdot h^2$

B: dry biomass (kg)

Table 68. Multiple regression analysis for *Phoenix dactilifera*

Resisual biomass versus diameter at breast height (dbh)			
Type of equation	R^2	sd	MAE
Linear	0.00	11.59	9.23
Quadratic	0.00	11.58	9.22
Resisual biomass versus crown diameter (dc)			
Type of equation	R^2	sd	MAE
Linear	0.07	11.15	8.55
Quadratic	0.06	11.19	8.57
Resisual biomass versus total tree height (h)			
Type of equation	R^2	sd	MAE
Linear	0.02	11.44	9.04
Quadratic	0.03	11.38	8.99

R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error

The low R^2 in Table 68 indicate that there is no interdependence between residual biomass and any of the examined variables.

Table 69. Significance of explicative variables for biomass prediction of *Phoenix dactilifera*

			Estimate	Standard error	T statistic	P-Value
B versus dbh	Linear model	Constant	36.6599	14.6076	2.50965	0.0186
		dbh	-0.011933	0.328467	-0.0363294	0.9713
	Quadratic model	Constant	36.7375	7.46454	4.9216	0.0000
		dbh^2	-0.000304493	0.00360809	-0.0843919	0.9334
B versus dc	Linear model	Constant	17.6568	13.0508	1.35292	0.1877
		dc	2.46572	1.71858	1.43474	0.1633
	Quadratic model	Constant	27.0116	6.99324	3.86254	0.0007
		dc^2	0.15821	0.115585	1.36877	0.1828
B versus h	Linear model	Constant	30.6891	6.95883	4.41009	0.0002
		h	0.545904	0.66299	0.823396	0.4178
	Quadratic model	Constant	32.9225	3.93154	0.37396	0.0000
		h^2	0.0291616	0.0298689	0.976321	0.3379

B: dry biomass (kg); dbh: diameter at breast height (cm); dc: crown diameter (m); h: total tree height (m)

The P-values in Table 69 are greater or 0.05. There is not a statistically significant relationship between the variables at the 95.0% or higher confidence level.

In addition, regression models for predicting residual biomass were tested from combinations of variables such us diameter at breast height, crown diameter and total tree height. The best result is shown in the Table 70 and 71. A higher R^2 value (R^2=0.67) was obtained. The combination of these parameters improved the prediction models obtained from one variable.

Table 70. Regression model to describe the relationship between residual biomass and dendrometric variables for *Phoenix dactilifera*

Equation *	R^2	sd	MAE
$B = 64.4552 - 19.651 \cdot h + 20.2859 \cdot hc + 1.70061 \cdot h^2 - 2.08599 \cdot h \cdot hc$	0.67	6.00	4.01

B: dry biomass (kg); R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error; hc: distance from soil to the crown (m); h: total tree height (m); * best equation validated with independent data

Table 71. Significance of explicative variables for biomass prediction for *Phoenix dactilifera*

Dependent variable: B
Independent varable: h. hc, h^2, $h \cdot hc$

Parameter	Estimate	Standard error	T statistic	P-Value
Constant	64.4552	19.137	3.36809	0.0039
h	-19.651	6.43542	-3.05357	0.0076
hc	20.2859	5.97769	3.3936	0.0037
h^2	1.70061	0.462525	3.6768	0.0020
$h \cdot hc$	-2.08599	0.54423	-3.83293	0.0015

B: dry biomass (kg); hc: distance from soil to the crown (m); h: total tree height (m)

The P-values are less than 0.05, for that there is a statistically significant relationship between the variables at the 95.0% confidence level.

Prediction models calculated from the apparent volume of the crown were analyzed. As observed in Table 72, there is no relationship between the crown volume model and the amount of dry biomass obtained from pruning.

Table 72. Regression model to describe the relationship between biomass and independent variable crown volume for *Phoenix dactilifera*

Type of model	Equation	R^2	sd	MAE
Conical volume model	$B = 30.3555 + 0.0885565 \cdot V$ cone	0.07	11.17	8.65
Parabolic volume model	$B = 30.3555 + 0.0590377 \cdot V$ paraboloid	0.07	11.17	8.65
Hemispheric volume model	$B = 30.3535 + 0.048627 \cdot V$ hemisphere	0.06	11.23	8.65

B: dry biomass (kg); R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error

The conical and parabolic volume models present the same very low coefficient of determination. The parabolic model is described below (Table 73).

Table 73. Significance of explicative variables for biomass prediction of *Phoenix dactilifera*

Dependent variable: B				
Independent varable: V paraboloid				
Parameter	Estimate	Standard error	T statistic	P-Value
Constant	30.3555	4.63231	6.55299	0.0000
V paraboloid	0.0590377	0.0421119	1.40192	0.1728

B: dry biomass (kg)

An analysis of variance was done to compare both species of palm trees: *Phoenix dactilifera* and *Phoenix canariensis*. The results are presented in Figure 23.

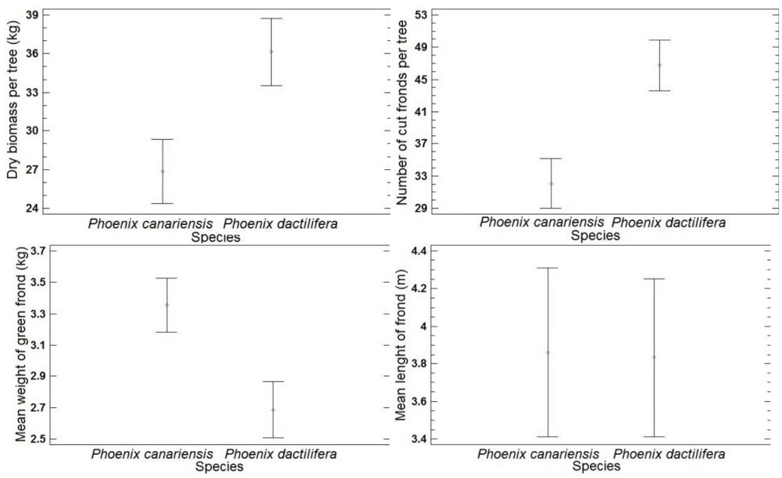


Figure 23. LSD intervals for the comparison of the residual biomass for *Phoenix dactilifera* and *Phoenix canariensis*: dry biomass per tree, number, mean weight and length of pruned leaves

Figure 23 demonstrates that the *Phoenix canariesis* has heavier leaves than the *Phoenix dactilifera*. While the *Phoenix dactilifera* is characterized with a higher number of cut fronds per palm.

The results demonstrate lack of interdependence between lonely examined parameters and quantity of yielded residual biomass. This is the consequence of the characteristics of palms. Palms being monocots have a different anatomy and form than other studied trees. The diameter at breast height does not increase with age. Therefore it is logical that no dependence can be seen between diameter at breast height and quantity of biomass. Moreover, the total tree height is never reduced during pruning operations as in this part, the youngest leaves are formed and also the terminal bud is located. Pruning this part would result in the death of the palm. Finally, the crown diameter practically does not decrease after the palm is pruned. This is caused by the characteristic form that palm leaves form in the canopy. The fronds of *Phoenix canariesis* are longer (mean 3.86 m) and heavier (mean 3.35 kg) comparing to *Phoenix dactilifera*. On the other hand, the study showed that the quantity of cut fronds per palm is higher in case of *Phoenix dactilifera* (mean 46.75 fronds).

When all prediction models for *Platanus hispanica, Morus alba*, *Sophora japonica*, *Phoenix canariensis* and *Phoenix dactilifera* were analysed, we reached the following conclusions. The results of this research cannot be compared directly to other studies as no data seem to be available or published on allometric equations for biomass prediction from pruning urban trees. However, some aspects may be similar to research conducted on all aboveground biomass estimates for forest and landscape trees. The results of this thesis are similar to other reports in that the dbh alone is a good predictor of biomass in the whole plant (McHale et al., 2009, Pillsbury et al., 1998, Eamus et al., 2000, Jenkins et al., 2004) and that its advantage over other parameters is associated with the accuracy, practicability and cost of measurement (Kuyah et al., 2012). In this study dbh when used as the only explanatory variable provided satisfactory estimation of biomass in case of *Platanus hispanica* and *Sophora japonica* yielding coefficients of determination R^2=0.80 and R^2=0.57, respectively. Similar to Ketterings et al., 2002, it was found, that including the total tree height in the prediction models improves the R^2 in contrast to the findings of Kuyah et al., (2012). When considering the crown diameter, good results were obtained for *Morus alba* street location (R^2=0.87), *Morus alba* park location (R^2=0.59) and *Platanus hispanica* (R^2=0.64). Even better results were observed, when including the crown volume in prediction models for *Morus alba* street location (R^2=0.90), *Morus alba* park location (R^2=0.59) and *Platanus hispanica* (R^2=0.78). Nevertheless, Kuyah et al., (2012) observe, that crown parameters are expected to increase the R^2 of prediction models but difficulties associated with measuring tree crown and its highly heterogeneous geometry are the reason of not including this parameter in equations. In contrast to other studies on all aboveground biomass from trees, a combination of all explanatory variables has been tested and led to improved results: *Morus alba* street location R^2=0.96, *Morus alba* park location R^2=0.88, *Platanus hispanica* R^2=0.93, *Sophora japonica* R^2=0.76, *Phoenix canariensis* R^2=0.88, *Phoenix dactilifera* R^2=0.67, respectively. Although very height coefficients were obtained, in many cases it may be complicated, costly and time consuming to measure these parameters. Moreover, the complexity of these models is a disadvantage over simple regression equations with only one variable. Information from other studies that calculated leaf-biomass from open grown urban trees based on equations derived from dbh and crown parameters indicated that estimates based on crown width gave better results than from diameter at breast height. Nevertheless, both may tend to overestimate biomass in cases as pruning (Gacka-Grzesikiewicz, 1980, Nowak, 1996). A study by Dobbs et al., (2011) estimated crown biomass by equations developed on data from randomized branch sampling. The findings of this work included, that some of the equations may overestimate biomass in smaller trees due to different growth rates of diameter and height.In addition, some studies have been carried out to calculate pruned biomass in agricultural trees. The study performed by Fernandez-Gonzalez (2010) calculated prediction models from different combinations of dendrometric variables, such as breast height diameter, crown diameter, total height or crown height. The R^2 obtained were between 0.6-0.95, therefore these equations gave similar level of coefficients of determination to those obtained in our study for predicting residual biomass for urban trees.

5.2. APPLICATION OF TLS FOR CALCULATION OF DENDROMETRIC PARAMETERS

5.2.1. Comparison of TLS data with direct measurements

Table 74 contains the values of tree height (h), distance from soil to the crown (hc), crown height (ch) and crown diameter (dc) of 30 specimens of *Platanus hispanica* obtained from terrestrial laser scanning and from manual *in situ* measurements.

Table 74. Tree parameters extracted from TLS point clouds and classical observations

Tree number	h (m)	h TLS (m)	hc (m)	hc TLS (m)	ch (m)	ch TLS (m)	dc (m)	dc TLS(m)
1	10.20	9.77	3.10	3.38	7.10	6.39	6.45	6.38
2	9.20	9.12	2.50	3.16	6.70	5.96	5.00	4.95
3	12.50	12.23	4.20	4.25	8.30	7.97	8.85	10.68
4	10.50	10.09	3.40	3.38	7.10	6.70	6.55	6.48
5	12.70	11.75	3.90	3.71	8.80	8.04	8.25	10.72
6	12.30	12.87	3.70	3.89	8.60	8.98	8.10	8.05
7	11.20	11.46	3.40	4.17	7.80	7.29	8.30	8.73
8	12.20	11.66	4.10	4.28	8.10	7.37	7.40	7.77
9	11.80	11.10	4.30	4.30	7.50	6.79	8.10	8.72
10	12.00	12.08	3.90	3.56	8.10	8.52	8.65	9.23
11	6.40	9.10	2.30	2.91	4.10	6.19	5.60	5.92
12	8.20	11.36	3.20	4.03	5.00	7.32	8.30	8.00
13	11.00	10.61	3.70	3.59	7.30	7.01	7.85	8.16
14	11.50	11.24	4.60	4.31	6.90	6.93	8.31	8.66
15	9.40	9.69	3.90	3.30	5.50	6.38	5.62	5.94
16	9.20	9.41	4.10	3.57	5.10	5.83	5.41	5.76
17	10.30	10.31	4.20	3.70	6.10	6.61	6.30	7.10
18	10.40	10.77	3.90	3.93	6.50	6.83	6.75	6.97
19	12.40	12.19	3.80	3.90	8.60	8.29	9.50	9.95
20	8.50	8.94	2.20	2.24	6.30	6.69	4.10	4.27
21	13.30	12.58	2.60	4.09	10.70	8.48	10.86	12.12
22	9.20	9.28	3.10	3.72	6.10	5.56	5.60	5.10
23	12.60	12.72	3.90	3.82	8.70	8.90	9.74	10.50
24	13.20	12.70	3.60	4.43	9.60	8.27	10.35	10.77
25	9.90	12.34	3.40	3.78	6.50	8.56	9.42	10.08
26	12.00	11.61	3.70	4.13	8.30	7.48	7.89	8.47
27	11.80	10.22	4.60	3.98	7.20	6.23	9.37	8.22
28	13.00	12.89	4.00	3.99	9.00	8.90	10.97	11.19
29	11.80	12.39	4.20	4.74	7.60	7.65	9.35	9.28
30	11.30	11.55	3.80	3.94	7.50	7.60	10.35	11.58
Maximum	13.30	12.89	4.60	4.74	10.70	8.97	10.97	12.12
Minimum	6.40	8.94	2.20	2.24	4.10	5.56	4.10	4.27
Mean	11.00	11.13	3.64	3.81	7.35	7.32	7.90	8.32
Standard deviation	1.67	1.27	0.62	0.49	1.44	0.99	1.83	2.12

To compare dendrometric parameters obtained with both methodologies an analysis of variance was performed.

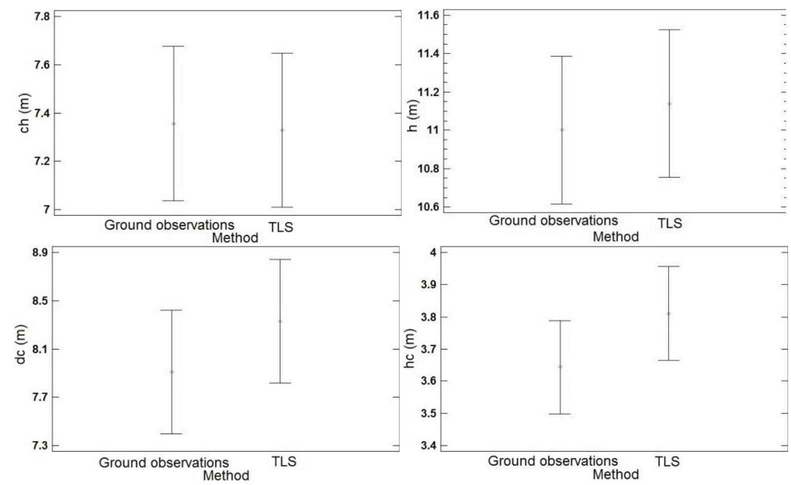


Figure 24. Intervals of statistical comparison of the dendrometric measurements carried out manually and by means of TLS for 30 sample trees: ch: crown height (m); h: total tree height (m); dc: crown diameter (m); hc: distance from soil to the crown (m);

The results indicate that there are no significant differences (P-values<0.05) within the analyzed parameters obtained with 2 different methods, although the average of total tree heights obtained in field trials is somewhat lower than the obtained by TLS. This may be caused by improper registration of the peak of the canopies due to the proximity of the scanner to sample trees. This may also indicate, that trees tend to be underestimated while ground-based measurements. The average crown diameter calculated manually in field trials is also somewhat lower than the extracted from TLS point clouds, however they do not present statistical differences in the ANOVA. One reason of underestimation may be attributed to the existence of obstructing elements in the form of neighbour trees. In many cases the border between branches of neighbour tree crowns is hard to define from ground level. On the other hand, it is considered, that values obtained with programming are very precise. These results point that classical methods give acceptable values. 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). In case of distance from soil to the crown the difference of the means may be explained by the criteria assigned for the selection of the canopy base.
An inter-comparison by means of regression models of structural parameters was made for data obtained with both methodologies (Figure 25). Coefficients of determination and mean absolute errors were determined.

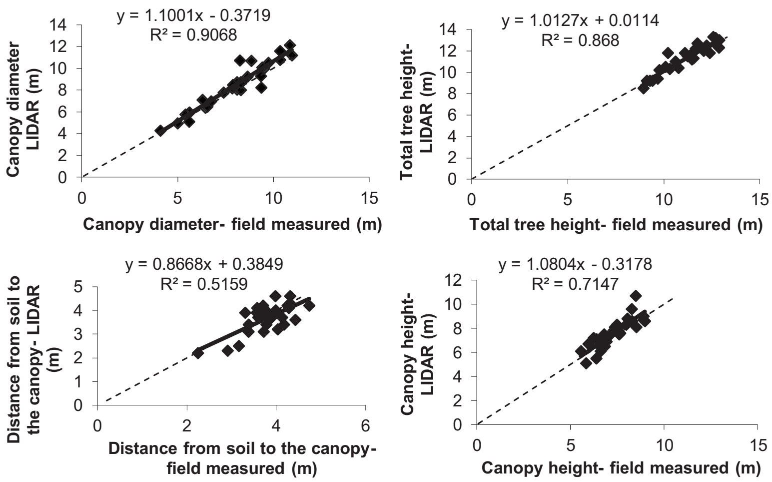


Figure 25. Inter-comparison of parameters obtained from TLS point clouds and ground observations for 30 sample trees: canopy diameter (m); total tree height (m); distance from soil to the crown (m); canopy height (m)

Figure 25 shows that the models highly explain the relation (R^2=0.90) between crown diameters and a good relationship between total tree heights (R^2=0.86). On the other hand, the models which relate the distance from soil and the crown results show the lowest levels of R^2 within both methodologies. This may be explained by the criteria assigned for the selection of the canopy base. In case of manual measurement as a 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 (A [No.] T.xyz) and (A [No.] .xyz) files containing 3D scans of tree trunks and total tree heights.

The analysis of two different methods of tree data collection in this study revealed some potential errors that should be considered for future crown structure studies. TLS data collection of crown physical dimensions on an individual tree level showed advantages and disadvantages of the technology. The tripod-mounted TLS scans may capture crown height ineffectively, because a part-point registration along the Z-axis (height) may occur in case of inaccurate TLS distance from target tree. This may lead to misestimating of total tree height. However, laser pulse reflection registers along the Y-axis (width) are very precise if not interfered with obstructing elements. The advantage of TLS approach is that it is quicker than time-consuming ground methods that run risk of potential observer error. In this study the ground-based and TLS-based approach was inter-compared. Crown diameter obtained by TLS strongly correlated with data obtained from ground observations with a coefficient of determination of R^2=0.90. On the other hand, the inter-comparison of both approaches for variable distance from soil to the crown indicated the lowest coefficient of determination of all analyzed physical tree dimensions (R^2=0.51). This may be caused by the difference in estimating the base of the canopy variable in both methodologies. As for canopy height (R^2=0.71), this variable is dependent from other two parameters namely total tree height and distance from soil to the crown. Any error committed when calculating the previously mentioned, influences the accuracy of this variable.

5.2.2. **Comparison of TLS data with crown volume**

Table 75 contains values of the crown volumes of 30 specimens of *Platanus hispanica* obtained from TLS data applying the four mentioned methods (global CH, CH layers, sections, voxel) and from field measurements applying solids of revolution (paraboloid, hemisphere, cone). As can be observed, the greatest values of volume calculated from TLS data were obtained using the global CH method, followed by the methods by sections and CH layers, which are very similar. The lowest volumes were obtained using the method based on voxels. This result can be explained by the fact, that some holes are not detected within the crown due to either the occultation by the external leaves - branches or their real absence (Figure 26). The volumes calculated using solids of revolution from classical dendrometry were lower than those obtained from TLS data.

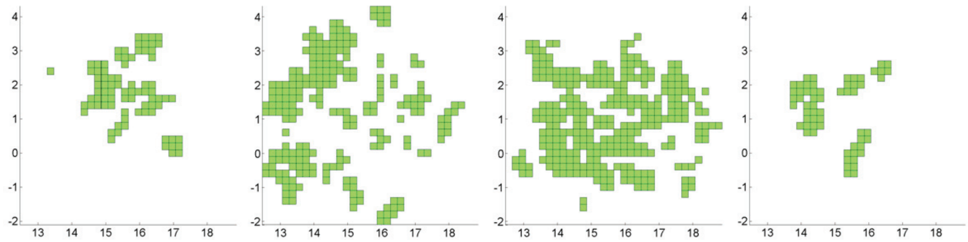


Figure 26. Position of the voxels in four horizontal sections at 3, 5, 7 and 9m height of tree

A large dispersion can be observed in the population (standard deviation), because the sampled trees had different degrees of development (growth). The young trees show a vertical development and the mature trees (most of the sampled trees) are characterized by a horizontal expansion while their geometric shape is close to a paraboloid. The values of skewness and kurtosis were close to 0 indicating a good approximation to the normal distribution. This fact is very important given that different analyzes to compare the volumes derived from classical dendrometry and TLS data are allowed.

Table 75. Volumes (m^3) obtained for each of the 7 methods of calculation and their basic statistics

	TLS				Field measured		
Tree number	Global CH	Ch layers	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
Standard deviation	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
Shapiro-Wilks test (P-value)	0.276	0.238	0.225	0.225	0.173	0.193	0.173

To compare the volume calculated by means of the different methods, the analysis of variance was carried out. The LSD intervals at 95 % are shown in the Figure 27. This comparison has been carried out in three phases:

- Comparison between dendrometric volumes,
- Comparison of the volumes obtained from the TLS,
- Comparison between dendrometric volumes and volumes calculated from TLS.

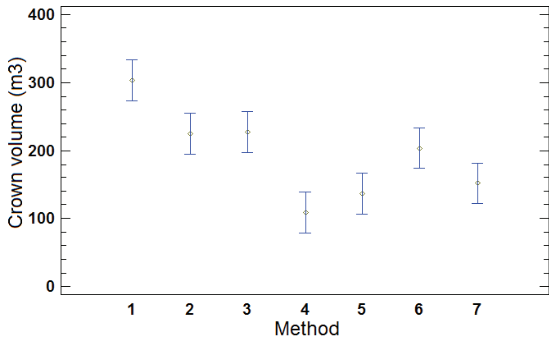


Figure 27. LSD intervals for calculation methods: 1-global CH; 2-CH layers; 3-sections; 4- voxel; 5- paraboloid; 6-hemisphere; 7-cone

As can be observed in the Table 76, the comparison between each two methods by linear regression models show high coefficients of determination. The analysis between methods applied to TLS data show 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 76. Equations and R^2 coefficient adjustment of the different calculation methods

Equation / R^2	Paraboloid	Hemisphere	global CH	CH Layers	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 Layers	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	

a) Comparison between dendrometric volumes

Figure 27 shows significant differences between the paraboloid and hemisphere. Figure 28 compares these volumes obtained using regression models. The dashed line represents the bisector line where both volumes are similar. It can be observed, that the crown volumes obtained from the paraboloid model are greater than those obtained from the hemispheric model, presenting points above the dashed line. However, some exceptions were found that could be explained considering some factors such as pruning or distance to buildings that could affect the growth and shape of the trees. Also, it can be observed that the points are distributed uniformly along the trend line, which shows the absence of anomalous points. In addition, there was proportionality among the volumes calculated using both geometric shapes according to equation (7). The results obtained from manual measurement at field of 30 specimens show that the average of the proportionality factor was 0.72 (Table 77) with a standard deviation of 0.13.

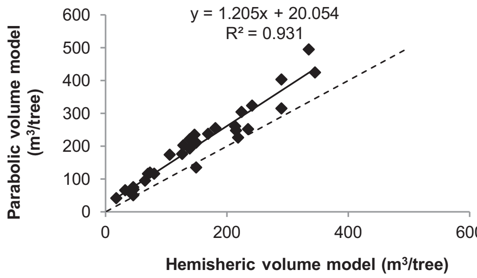


Figure 28. Paraboloid versus hemisphere volume of the crown (m^3) (30 sample trees)

Table 77. Statistical values of proportionality factor between the paraboloid crown model and hemisphere crown model

	dc/hc	K =2/3 * (dc/hc)
Mean	1.08	0.72
Standard deviation	0.20	0.13

dc: crown diameter (m); hc: distance from soil to the crown (m)

b) Comparison of the volumes obtained from the TLS

The global CH method provided the highest values of volumes (Figure 27). This is consistent with the nature of the method, which creates a solid surrounded by triangles whose vertices are the most exterior points of the point cloud data registered by the TLS. This volume includes all internal holes of the crown and external spaces between branches, generating an overestimation of the apparent volume.

The three-dimensional modelling by voxels gave the lowest values of volumes, approximately one third lower than the volumes obtained by the previous method. This can be explained by the fact that the rasterization is done according to 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, it is the method that performs best the actual shape of the crown with its branches and leaves. Nevertheless, it 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. (This limitation can be overcome using a greater scan resolution and number of base stations). For the mentioned reasons, these volume values are lower than actual volume, but can be used to calculate dendrometric variables, such as crown diameter and height or to be related with residual biomass.

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

The CH by layers and volume calculation by sections show very similar results and 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 convex hull. As can be observed in Table 76, the comparison between volumes generated using the CH by layers and section method 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 methods global CH and CH by layers (R^2 = 0.99). Good results were also obtained among volumes obtained using the CH layers and rasterization in voxel method (R^2 = 0.94).

c) Comparison between dendrometric volumes and volumes calculated from TLS

A comparative analysis was performed for finding relationships between the volumes obtained applying classical dendrometry (paraboloid) and TLS data processing (Figure 29 and Table 76). Values of R^2 were between 0.78 and 0.89. All volumes obtained from TLS data were higher than those obtained from the paraboloid model except for the volumes obtained from voxel quantification. It is also observed that the volumes of smaller trees were usually located near the diagonal. Greater differences were found for mature trees, what could be explained by the larger irregularities in their crowns. The relation between the paraboloid and volume calculation by sections gave the highest coefficient of determination (R^2) what means that this processing method could be used to estimate some dendrometric variables used to calculate the paraboloid volume such as crown diameter and height. It is important to note that the findings of this method are also very close to the CH layers method. The volumes obtained by quantification of voxels gave the lowest values, and the equations had the smallest R^2.

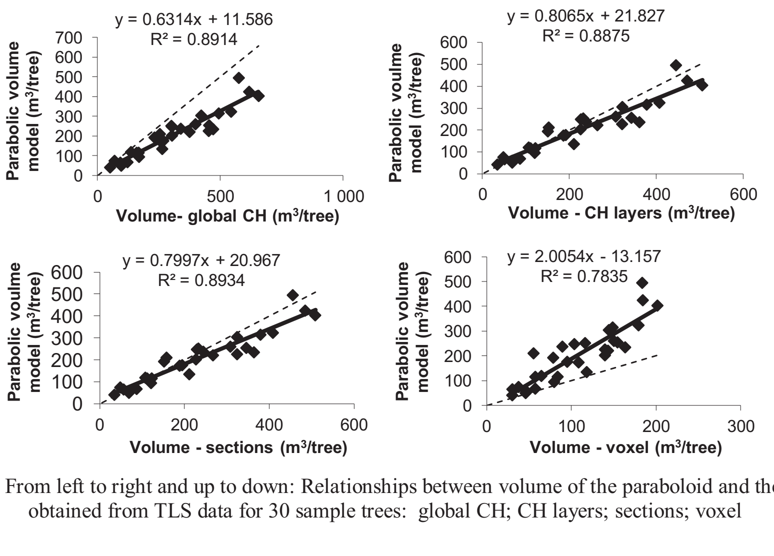


Figure 29. From left to right and up to down: Relationships between volume of the paraboloid and the volumes obtained from TLS data for 30 sample trees: global CH; CH layers; sections; voxel

An important variable to evaluate each method is the number of operations required and the processing time. Figure 30 shows a comparative analysis of this parameter for the 4 methods used to process the point clouds 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 small trees (minor number of points). However they were very significant for larger crowns.

The method based on voxel model, generated the highest variation of processing time, being almost three times the one required for the volume computation using the section method in big trees. This increase was not linear. The global Convex Hall and the Convex Hull by layers were the fastest methods, and they showed the lowest increase in the processing time for larger crown size. These variations were linear with a low gradient.

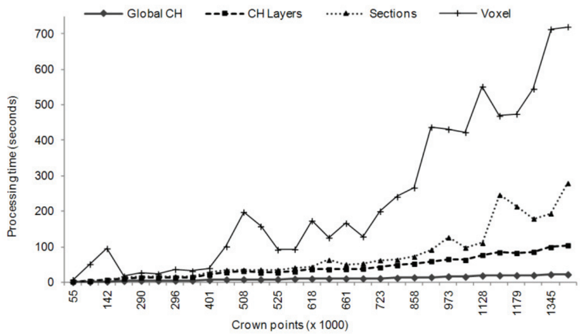


Figure 30. Processing time for each tree crown and the 4 methods applied to laser data

The relative peaks observed in the section method and voxel rasterization are explained by the distribution of points within a crown.

Concerning the voxel method, it is important to mention that a voxel with a high concentration of points and a voxel with few points are processed with only one operation. This means, that depending on point distribution, a crown with bigger number of points can have less or the same quantity of voxels and be processed in less or equal time than a crown with less TLS points. In general, the tendency is that the processing time increases with the number of points but occasionally can be found crowns with peak points.

In the case of the section method the external points are selected for crown volume calculation. Therefore, the distribution of points inside and in the external layer influences the processing time. It may occur that a crown with high number of points inside and few external points was processed faster than other crown with few TLS data but a lot of external points.

5.2.3. **Prediction of residual biomass from TLS data**

Pruned biomass was correlated with 4 methods of crown volume calculations extracted from TLS point clouds (Figure 31).

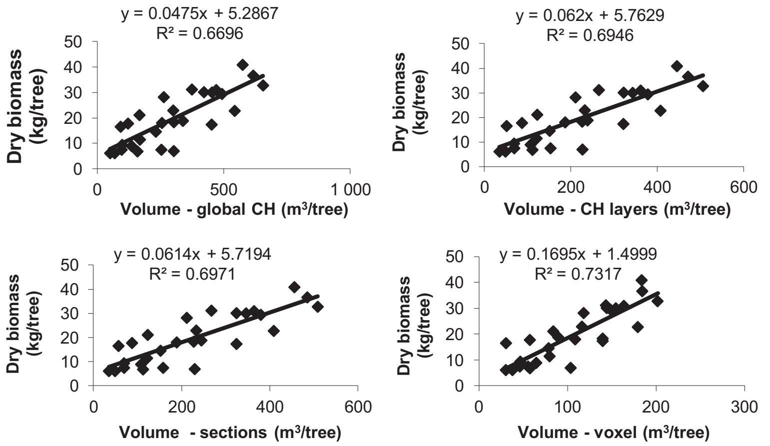


Figure 31. From left to right and up to down: Relationship between 4 methods of TLS volume calculation and yielded biomass from 28 sample trees: global CH; CH layers; sections, voxels

The results are similar for all analysed models. The best coefficient (R^2=0.73) is observed between biomass and volume processed from voxels. This is explained by the accuary of voxel method and best adjustment to crown architecture. However, minor differences of coefficients in all analysed models indicate that less time-consuming processing methods give satisfying results (run risk of low error). Biomass obtained from pruning was also correlated with goemetrical crown volumes (Figure 32).

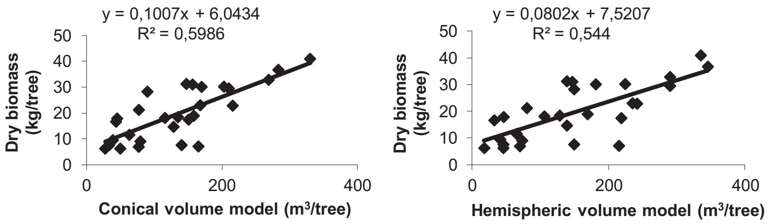


Figure 32. Relationship between 2 methods of volume calculation (cone, hemisphere) and yielded biomass from 28 sample trees

The conical and parabolic volume models are proportional and indicate a coefficient of R^2=0.59. The result is lower than the relation obtained with volumes extracted from point clouds. This explains higher precision of TLS over ground-level measurement.

The inter-comparison of pruned biomass with volumes extracted from point clouds revealed the highest accuracy of the voxel method and its adjustment to crown architecture (R^2=0.73). However minor differences of coefficients in all analysed models indicated, that less time-consuming processing methods give similar results and run risk of low error. The results obtained with geometrical volume models presented lower coefficients of 0.59 and 0.54, respectively. Results obtained with both methodologies demonstarte relationship between examined parameters and possibility of predicting biomass from volume.

The results concerning residual biomass prediction from pruning urban trees obtained from processing point clouds cannot be compared directly to other studies as no published data have been found on the topic. Nevertheless, studies exist on LIDAR application to estimate crown structure, stem volume.

5.3. ENERGY CHARACTERIZATION OF THE RESIDUES

5.3.1. Elemental composition

In Table 78 are presented the values of elemental composition and gross calorific value of the studied biomass dried in stove and wet up to 10%.

Table 78. Analysis of elemental composition of examined biomass

Variable	Species	Drying process	Average	Standard deviation	Standard skewness	Standard kurtosis	Maximum	Minimum
GCV (kJ/kg)	*Morus alba*	W10	17127.62	157.02	-1.04	0.04	17301.25	16834.74
	Morus alba	Dry	18192.86	554.08	0.37	-0.60	19099.12	17396.23
	Phoenix canariensis	W10	14655.71	742.24	0.74	-0.81	15722.63	14000.91
	Phoenix canariensis	Dry	16029.23	377.56	-1.57	1.67	16434.33	15321.38
	Phoenix dactilifera	W10	15134.07	1193.27	-0.81	-0.80	16286.63	13452.39
	Phoenix dactilifera	Dry	16975.19	444.84	1.00	0.86	17752.29	16466.55
	Platanus hispanica	W10	17513.76	356.56	-0.01	-1.10	17972.79	17084.94
	Platanus hispanica	Dry	18952.47	556.93	-0.08	-0.84	19707.47	18195.79
	Sophora japonica	W10	17970.48	198.40	1.16	-0.03	18317.13	17746.43
	Sophora japonica	Dry	19615.67	100.75	-1.20	1.66	19754.33	19418.78
% C	*Morus alba*	W10	44.54	0.38	-0.15	-0.88	45.0	44.0
	Morus alba	Dry	48.22	0.67	-0.11	-0.37	49.3	47.2
	Phoenix canariensis	W10	39.11	1.45	0.52	-0.90	40.9	37.5
	Phoenix canariensis	Dry	42.36	1.71	0.65	-0.25	45.0	40.3
	Phoenix dactilifera	W10	39.43	1.96	-0.69	-0.82	41.3	36.7
	Phoenix dactilifera	Dry	44.36	1.07	0.14	-0.78	45.7	43.0
	Platanus hispanica	W10	44.1	0.58	0.41	-0.47	45.0	43.3
	Platanus hispanica	Dry	48.48	0.64	0.41	-1.22	49.3	47.8
	Sophora japonica	W10	45.66	0.53	-0.10	1.15	46.6	44.7
	Sophora japonica	Dry	49.15	0.63	-0.23	-0.16	50.1	48.1
% H	*Morus alba*	W10	6.36	0.07	0.48	-0.94	6.45	6.26
	Morus alba	Dry	5.92	0.03	-0.28	-0.73	5.97	5.87
	Phoenix canariensis	W10	5.65	0.26	-0.58	-0.88	5.9	5.3
	Phoenix canariensis	Dry	5.50	0.47	-0.55	0.08	6.09	4.75
	Phoenix dactilifera	W10	5.99	0.27	-0.58	-0.90	6.26	5.62
	Phoenix dactilifera	Dry	5.78	0.23	-0.64	-0.98	6.0	5.48
	Platanus hispanica	W10	5.83	0.08	0.89	0.72	5.99	5.73
	Platanus hispanica	Dry	5.77	0.00	-0.51	-0.27	5.87	5.69
	Sophora japonica	W10	6.54	0.06	0.28	0.39	6.67	6.44
	Sophora japonica	Dry	6.17	0.10	-1.37	1.35	6.3	5.97
%N	*Morus alba*	W10	0.60	0.14	0.64	-0.88	0.83	0.45
	Morus alba	Dry	0.86	0.13	-1.04	-0.60	1.01	0.62
	Phoenix canariensis	W10	0.33	0.02	0.18	-1.19	0.36	0.31
	Phoenix canariensis	Dry	0.41	0.01	0.85	-0.19	0.44	0.40
	Phoenix dactilifera	W10	0.49	0.02	0.03	-0.40	0.53	0.45
	Phoenix dactilifera	Dry	0.61	0.03	1.02	-0.68	0.66	0.58
	Platanus hispanica	W10	0.67	0.12	0.15	-1.08	0.85	0.51
	Platanus hispanica	Dry	0.78	0.13	-0.16	-1.02	0.94	0.61
	Sophora japonica	W10	0.90	0.21	1.69	0.78	1.34	0.72
	Sophora japonica	Dry	1.16	0.17	0.76	-0.64	1.42	0.98
% S	*Morus alba*	W10	0.04	0.00	-1.67	1.54	0.05	0.04
	Morus alba	Dry	0.05	0.00	0.42	-0.57	0.05	0.04
	Phoenix canariensis	W10	0.44	0.07	0.02	-0.47	0.54	0.34
	Phoenix canariensis	Dry	0.48	0.06	0.87	-0.50	0.59	0.42
	Phoenix dactilifera	W10	0.45	0.15	1.40	0.56	0.32	0.73
	Phoenix dactilifera	Dry	0.43	0.03	0.87	-0.86	0.48	0.40
	Platanus hispanica	W10	0.05	0.00	-0.82	-0.74	0.05	0.04
	Platanus hispanica	Dry	0.05	0.00	0.63	-0.11	0.06	0.04
	Sophora japonica	W10	0.05	0.00	-1.92	1.85	0.05	0.03
	Sophora japonica	Dry	0.05	0.00	-0.51	-0.45	0.05	0.04
% bark	*Morus alba*		9.49	3.83	1.20	-0.17	17.82	3.13
	Platanus hispanica		13.05	4.80	1.74	0.92	25.43	6.57
	Sophora japonica		5.29	3.53	1.49	-0.18	13.46	0.14

W10: sample up to 10% moisture content in wet basis; GCV: gross calorific value (kJ/kg); C: carbon (%); H: hydrogen (%); N: nitrogen (%); S: sulfur (%)

As it can be observed, all variables show standard kurtosis and standard skewness between -2 and + 2. This fact means that all of them follow a normal distribution, which is essential for the analysis. The average GCV of analyzed species range between 14-20 MJ/kg depending on moisture content what gives similar results to those published by Gillon et al., (1997) on residuals from landscape maintenance of broad-leaved species (18.80-21.10 MJ/kg) and by Yin (2011) for biomass (14-23 MJ/kg). These results are also approximated to those found by FAO (2004) on net calorific value of road side green 14,1MJ/kg and Castells (2005) for park residuals and wood slightly above 4000 kcal/kg. The GCV found in this thesis are similar to those for agricultural residuals (15-17 MJ/kg) and to woody materials (18-19 MJ/kg) (Vargas Moreno, 2012).

To compare the GCV of different species, the analysis of variance was carried out. The LSD intervals at 95 % are shown in the Figure 33. It is observed, that the GCV is significantly different among the studied species.

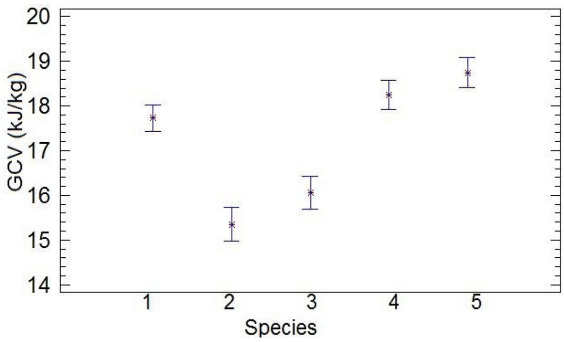


Figure 33. LSD intervals for GCV of species: 1-*Morus alba*; 2-*Phoenix canariensis*; 3-*Phoenix dactilifera*; 4-*Platanus hispanica*; 5- *Sophora japonica*

The dependence of the studied variables is shown in the Table 79. It can be noted that moisture content, %C, and %H have a high influence in the Gross Calorific Value (GCV) when are considered lonely what is also observed in other studies (Callejon et al, 2011, Telmo et al., 2010). Nevertheless, it is important to point that the high %H is related with the moisture content of the material, given that the water has as formula H_2O. The water content in the pores of the biomass modifies the weight of the material and the ratio of the other elements in the sample composition.

In the Table 78 can be seen that the stove-dried samples present higher mean concentration of carbon and calorific value while the %H generally decreases in dried environment. This is explained by the additional energy that must be used for H_2O evaporation for samples with moisture contents above 0%. The palms are observed to have the lowest calorific values and %C within the studied species. On the other hand they present 10 times higher concentration of sulphur then other sample trees. Sulphur can be dependent from high concentration in soil and air environment. The results also indicate that

Sophora japonica is the species with highest values within most studied parameters (excluding %S). The concentration of C and H in the studied biomass was approximately 40-50% and 5.5-6.5% what is found in the range for published data (C=42-71%, H= 3-11%) (Vassilev et al., 2010). The N and S concentration in the examined residuals estimated at the level of 0.3-1.1% and 0.04-0.48% are low comparing to those found in literature for biomass (N=0.1-12%, S=0.01-2.3%) (Vassilev et al., 2010, Khan et al., 2009). This result is an advantage, as high concentration of N and S produces negative impact on environmental due to the emission of nitrogen oxides, sulfur dioxide and sulfur trioxide during combustion (Khan et al., 2009; Elmo et al., 2010).

Table 79. Multidimensional analysis of studied elemental composition

Morus alba	% Moisture content	% C	% H	% N	% S	GCV (kJ/kg)
% Moisture content		-0.9672*	0.9789*	-0.7399*	-0.4512	-0.7750*
% C	-0.9672*		-0.9248*	0.8505*	0.4747	0.6495*
% H	0.9789*	-0.9248*		-0.6855*	-0.4823	-0.8530*
% N	-0.7399*	0.8505*	-0.6855*		0.6278*	0.4730
% S	-0.4512	0.4747	-0.4823	0.6278*		0.5724
G CV(kJ/kg)	-0.7750*	0.6495*	-0.8530*	0.4730	0.5724	
Phoenix canariensis	% Moisture content	% C	% H	% N	% S	GCV(kJ/kg)
% Moisture content		-0.7118*	0.1985	-0.9013*	-0.3062	-0.7900*
% C	-0.7118*		0.3719	0.5653	-0.0111	0.8093*
% H	0.1985	0.3719		-0.0612	-0.2266	0.0258
% N	-0.9013*	0.5653	-0.0612		0.4111	0.5777
% S	-0.3062	-0.0111	-0.2266	0.4111		-0.1626
GCV(kJ/kg)	-0.7900*	0.8093*	0.0258	0.5777	-0.1626	
Phoenix dactilifera	% Moisture content	% C	% H	% N	% S	GCV(kJ/kg)
% Moisture content		-0.8800*	-0.4112	-0.8867*	0.0044	-0.7576*
% C	-0.8800*		0.7507*	0.8388*	-0.1829	0.9346*
% H	-0.4112	0.7507*		0.5483	-0.0973	0.7162*
% N	-0.8867*	0.8388*	0.5483		0.3413	0.6669*
% S	0.0044	-0.1829	-0.0973	0.3413		-0.4006
GCV(kJ/kg)	-0.7576*	0.9346*	0.7162*	0.6669*	-0.4006	
Platanus hispanica	% Moisture content	% C	% H	% N	% S	GCV(kJ/kg)
% Moisture content		-0.9619*	0.4550	-0.3955	-0.3119	-0.8210*
% C	-0.9619*		-0.2451	0.5867*	0.3198	-0.9221*
% H	0.4550	-0.2451		0.3346	-0.3913	-0.0822
% N	-0.3955	0.5867*	0.3346		-0.0111	0.7832*
% S	-0.3119	0.3198	-0.3913	-0.0111		0.2210
GCV(kJ/kg)	-0.8210*	0.9221*	-0.0822	0.7832*	0.2210	
Sophora japonica	% Moisture content	% C	% H	% N	% S	GCV(kJ/kg)
% Moisture content		-0.9823*	0.9714*	-0.6481	-0.5947	-0.9825*
% C	-0.9823*		-0.9427*	0.7122*	0.5295	0.9834*
% H	0.9714*	-0.9427*		-0.4907	-0.5908	-0.9327*
% N	-0.6481	0.7122*	-0.4907		0.0520	0.7522*
% S	-0.5947	0.5295	-0.5908	0.0520		0.4682
GCV(kJ/kg)	-0.9825*	0.9834*	-0.9327*	0.7522*	0.4682	

* pares of variables with P-values lover then 0.05; GCV: gross calorific value (kJ/kg); C: carbon (%); H: hydrogen (%); N: nitrogen (%); S: sulphur (%)

For indirect GCV calculation, prediction models from ratios of C, H, N, and S were developed. These models have high importance in the industry because the GCV of material is used in boilers and is usually unknown due to the influences of moisture content as demonstrated (Table 78 and 79). The GCV determination with adiabatic calorimeter AC-500 takes 20 min/sample, and moisture content measurement takes 24 h using the norm UNE. According to experience with LECO CHN Truspec analyzer, the time of the elemental analysis is 5 min/sample. Therefore, the indirect measurement using regression equation from the ratios C, H, N and S lead to faster and consequently cheaper determinations (Table 80).

Table 80. Prediction models for indirect calculation of gross calorific value

Species	Function	R^2	sd	MAE
Morus alba	$GCV = 3674.57 + 302.93 \cdot C$	0.66	421.97	328.48
Phoenix canariensis	$GCV = 1295.20 + 344.77 \cdot C$	0.74	484.75	338.31
Phoenix dactilifera	$GCV = -3333.57 + 571.06 \cdot C - 8194.02 \cdot N$	0.93	349.65	253.92
Platanus hispanica	$GCV = 4189.23 + 269.63 \cdot C + 2138.94 \cdot N$	0.95	201.20	158.40
Sophora japonica	$GCV = -2080.66 + 439.47 \cdot C$	0.96	174.26	132.758

GCV: gross calorific value (kJ/kg); C: carbon (%); N: nitrogen (%)

All models present high R^2 and can be used to calculate the gross calorific value without the need of a calorimeter. This allows shortening the measurement process when necessary. The P-value in all explicative variables was lower than 0.05.

5.3.2. Determination of moisture content

Figures 34, 35, 36, 37 and 38 show the variation of moisture content during the evaluation of the drying process carried out in both open-air drying conditions. It is observed that the minimum moisture content in open-air was obtained between 25-40 days.

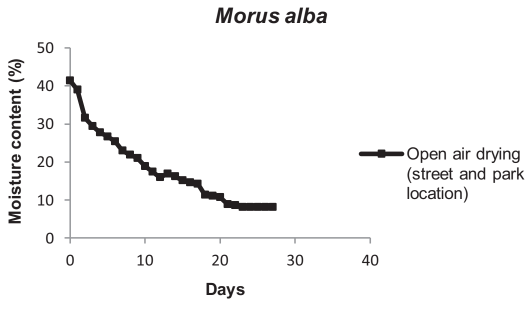


Figure 34. Drying curve for *Morus alba*

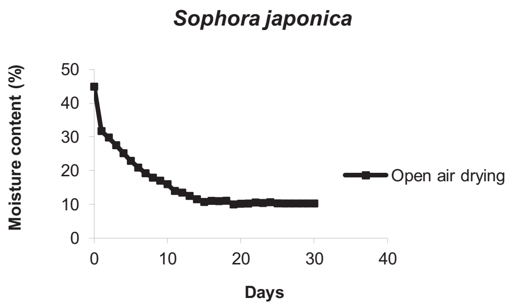


Figure 35. Drying curve for *Sophora japonica*

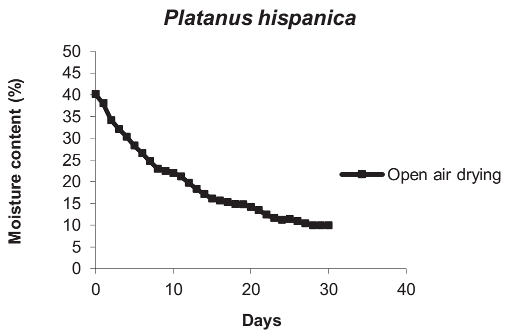


Figure 36. Drying curve for *Platanus hispanica*

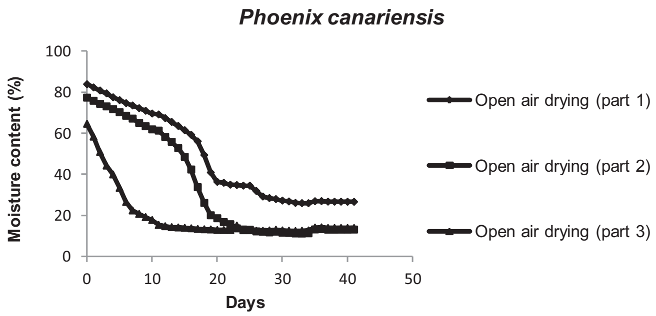


Figure 37. Drying curve for *Phoenix canariensis*

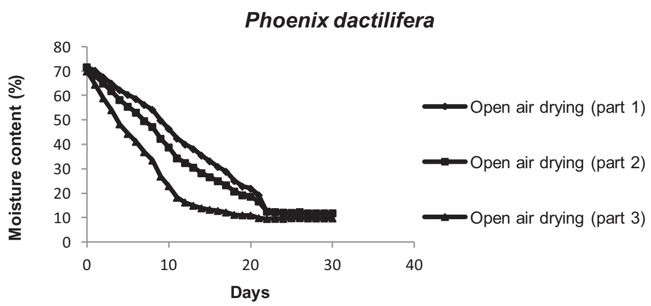


Figure 38. Drying curve for *Phoenix dactilifera*

5.3.3. **Determination of wood density**

In Table 81 can be observed that the species with highest mean density value is the *Sophora japonica.* According to published data *Morus alba* yields a medium-weight hardwood with density 670-850 kg/m^3 while *Platanus hispanica* 625 kg/m^3 (World Agroforestry Center, 2012). Wood density varies depending on growth conditions and part of the tree measured. The main stem is characterized with higher density than the branches what may explain the lower results obtained in this study.

Table 81. Density of analyzed species

Species	Mean (g/cm^3)	sd
Morus alba	0.60	0.04
Phoenix canariensis	0.65	0.14
Phoenix dactilifera	0.77	0.07
Platanus hispanica	0.50	0.14
Sophora japonica	0.86	0.19

sd: standard deviation

To compare the wood densities of different species, the analysis of variance was carried out. The LSD intervals at 95 % are shown in the Figure 39. The wood density is significantly different among the studied species.

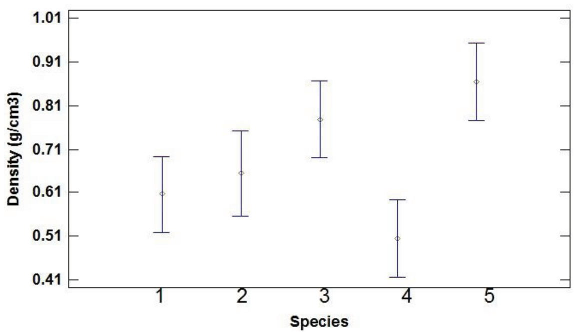


Figure 39. LSD intervals for wood density of species: 1-Morus alba; 2-Phoenix canariensis; 3-Phoenix dactilifera; 4- Platanus hispanica; 5- Sophora japonica

6. CONCLUSIONS

In this work has been found, that significant quantities of lignocellulosic residual biomass with possible energy and industrial end can be obtained from pruning urban forests.

Furthermore, indirect techniques for quantification of residual lignocellulosic biomass coming from mainetenance operations have been evaluated for the most important species of Mediterranean areas: *Morus Alba, Phoenix canariensis, Phoenix dactilifera, Platanus hispanica* and *Sophora japonica*. For this, three aproaches have been followed:

Firstly, prediction models based on allometric relationships between dendrometric parameters of the trees and quantity of yielded biomass have been developed. Secondly, a dendrometry characterization has been done. Its objetive was to allow calculating the actual volume of the branches from their base diameter and length. Thirdly, Terrestrial Laser Scanner (TLS) techniques have been evaluated. This approach led to substituting destructive sampling with every time more accurate, indirect methods.

This study has focused on biomass proceeding from pruning operations of urban forests. Numerous results of this thesis are a novel contribution to biomass research as no similar studies seem to be available or published.

6.1. ALLOMETRIC MODELS TO QUANTIFY RESIDUAL BIOMASS

Development of allometric equations applicable to urban forests is critical for non-destructive biomass estimation. It has been demonstrated that the residual biomass can be predicted from dendrometric variables in the studied species. The best functions have been obtained when several variables were combined in quadratics models. In case of *Platanus hispanica* the best explicative variables were diameter at breast height and crown diameter, or the apparent volume of tree crown obtained from conical model, which explained until 87% and 90 % of the population variability respectively. For *Morus alba*, significant differences have been found between trees located in streets and trees located in parks for all examined dendrometric parameters. The park location trees were bigger according to all examined variables. This influenced in the residual biomass quantity obtained from pruning, which was only formed by wood. Good results have been also found when correlating apparent crown volume with kilograms of yielded residual. *Morus alba, Platanus hispanica, Sophora japonica, Phoenix canariensis* and *Phoenix dactilifera* gave good models for predicting dried pruned biomass when the diameter at breast height, crown diameter, total height, and crown height were combined as explicative variables.

The obtained equations are a new tool for prediction of pruned residuals and can be used for biomass inventories in urban areas, planning the collection of these residues, and to establish policies for using these materials as feedstock.

Palm trees were those with greatest difficulty to be approximated to prediction models.

6.2. DENDROMETRIC CHARACTERIZATION OF BRANCHES

Two techniques have been evaluated to calculate the actual volume of the cut branches from their base diameter and length: using a form factor and volume functions. These, allow calculating the biomass when the branches cannot be weighted or they are in big bundles.

It has been verified that volume functions lead to better approximation to the actual volumes than the use of the form factor.

When the form factor is used to calculate the actual volume of a branch, the average must be used taking into account big dirpersion that exists in the obtained values. It has been found, that the form factor does not follow a tendency with variation of the base diameter and the length of the branch.

6.3. TERRESTRIAL LASER SCANNER (TLS) TECHNIQUES

Four procedures to calculate the canopy volume from modelling three-dimensional point clouds obtained by terrestrial laser scanner (TLS) have been developed and analyzed. After removing the noise error in the point clouds and separating the scan into individual tree files, 4 methods of volume calculation have been evaluated: *global convex hull* for the entire point cloud that forms the crown; *convex hull by layers* of 5cm height in the XY plane; triangulation by XY flat *sections*, and discretization of the point cloud in small elements of volume (*voxel*). Developed methods for apparent crown volume calculation allow obtaining high approximation to real crown shape.

It has been demonstrated that the volumes of smaller trees calculated from laser scanner have usually better proportionality to classical paraboloid volume than the bigger ones, due to their smaller irregularities. The processing method based on calculation by sections and the paraboloid method had the maximum coefficient of determination to calculate crown volume values. Considering the parameters of this geometric shape, this method could be also suitable to define 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 layers method.

The methods based on volume calculation by sections and Convex Hull by layers minimize the overestimation generated by the global Convex Hull method. The voxel method provided the smallest values of volumes and it was considered the best approximation to the real shape of the crown. This fact is caused by the partial detection of the structures in the inner part and complete detection in the outer part of canopy. This is not achieved with the other methods. For this reason, it is considered that the voxel method is the most accurate to estimate the biomass of the tree. However, the occultation of points inside of the crown by external leaves and branches can be a limitation for the use of this method to calculate actual volume. Other disadvantage is the higher computational time used to perform the calculations. In contrast, the global Convex Hull and the Convex Hull by layers are the fastest methods, and they show a lower increase in the processing time with bigger crown size.

All studied methods applied to TLS data have showed high correlation with the volumes obtained with the classical geometric models. These models have been related with variables used for plantation management, such as: amount of residual biomass from pruning. The methods developed in this study from TLS data may involve an important advance for the management of the studied trees.

Studies on TLS data demonstrate advantage over time-consuming direct tree measurement:

- Destructive sampling is substituted with accurate, indirect methods,
- Ground-level labour-intensive inventory practices are replaced with high data collection capacity remote sensing systems. TLS data can be used for precise characterization of vegetation architecture and yielded biomass at individual tree level. This approach eliminates risk of potential observer error,
- Introduced for applications in urban forests, TLS systems allow three-dimensional modelling and geometrical characterization of trees, making it easier to develop management systems based on precise information.

6.4. WOOD CHARACTERIZATION

Characterization of physical and chemical properties of pruned materials in order to evaluate their suitability for energy and industrial applications has been made. The evaluation of drying process has been studied. The *Morus alba*, *Platanus hispanica* and *Sophora japonica* species had around 45% moisture content in wet basis while the *Phoenix canariensis* and Phoenix dactilifera reached more than 70% of moisture content in wet basis. The highest density of all species presented *Sophora japonica* (0.86 g/cm^3).

C, H, N, S determination allows developing indirect methods to calculate the gross calorific value of the materials at different moisture content with high precision. The applicability of these indirect methods is justified by the long time taken in direct analysis by an adiabatic calorimeter.

On the other hand, the C, H, N, S determination allows also evaluating environmental benefits by the reduction of carbon dioxide emissions when these materials are used as a biofuel. Nevertheless, other benefits should be considered, such as conservation of landfill space, reduction of waste disposal cost and reduction of pressure on forests. From an environmental point of view, the increased recycling of recovered urban wood residual biomass can be seen as a positive evolution because it leads to incensement of the total volume of CO_2 stored as wood-based products, enlarging the life-cycle of the fixed carbon in the new recycled products.

Due to the continuing expand of urban land, the increasing expansion of urban forests is predictable. Taking into account reasons of safety, aesthetics and increasing environmental awareness the case of this study is found important for the future.

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8. PUBLICATIONS AND CONGRESSES

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Velázquez-Martí B., Sajdak M., López-Cortés I., Fernández-Sarría A., Estornell J. Fernández-Sarría A., Estornell, J. 2012. Prediction models to estimate prunned biomass of *Platanus hispanica* to do raw material surveys from urban systems. Forest Science.

Velázquez-Martí B., Sajdak M., López-Cortés I. Available residual biomass obtained from pruning of Morus alba trees cultivated in urban forest. Renewable Energy.

Fernandez-Sarría A., Martínez L., Velázquez-Martí B., Sajdak M., Estornell J., Recio J.A. 2012. Different methodologies for calculating crown volume of Platanus hispanica trees by terrestial laser scanner and comparison with classical dendrometric measurements. Computers and Electronics in Agriculture.

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9. ANNEX

Table 82. Field data sheet 1

TEST DETERMINATION OF BIOMASS COMING FROM PRUNING OPERATIONS OF PALM TREES

GENERAL INFORMATION DATE

Species:	
Variety:	
Location:	Province:

Contact person		
Address		
Telephone		Mobile:
Email		

TREE MANAGEMENT INFORMATION

Biomass from pruning operations

Date of last pruning operations ______

Type of previous pruning operations______

Tree number	
Diameter at breast height (cm)	
Crown diameter (m)	
Distance from soil to the crown (m)	
Total tree height (m)	
Number of cut leaves	

Green leaves	Weight (kg)	Length (cm)	Dry leaves	Weight (kg)	Length (cm)
Leaf 1			Leaf 1		
Leaf 2			Leaf 2		
Leaf 3			Leaf 3		
Leaf 4			Leaf 4		
Leaf 5			Leaf 5		
Leaf 6			Leaf 6		
Leaf 7			Leaf 7		
Leaf 8			Leaf 8		
Leaf 9			Leaf 9		
Leaf 10			Leaf 10		
Average			Average		

Table 83. Field data sheet 2

TEST DETERMINATION OF BIOMASS COMING FROM PRUNING OPERATIONS

GENERAL INFORMATION DATE

Specie:	
Variety:	
Location:	Province:

Contact person		
Address		
Telephone		Mobile:
Email		

TREE MANAGEMENT INFORMATION

Biomass from pruning operations

Date of last pruning operations ______

Type of previous pruning operations______

Tree number	Tree 1	Tree 2	Tree 3	Tree 4	Tree 5
Diameter at breast height (cm)					
Crown diameter (m)					
Distance from soil to the crown (m)					
Total tree height (m)					
Weight 1 (kg)					
Weight 2 (kg)					
Weight 3 (kg)					
Weight 4 (kg)					
Weight 5 (kg)					
Weight 6 (kg)					
Weight 7 (kg)					
Weight 8 (kg)					
Weight 9 (kg)					
Weight 10 (kg)					
Average (kg)					

Table 84. Validation data

Species	New equation (25 sample trees)	Number of validation data (sample trees)	T-Student	P-Value
Morus alba street location	$B = 10.288 + 0.0256723 \cdot dbh^2 - 0.182728 \cdot dbh \cdot h - 3.18406 \cdot dc \cdot hc + 1.95276 \cdot h \cdot dc$	5	0.0148328	0.988529
Morus alba park location	$B = -1.8355 - 3.04043 \cdot dc \cdot h + 17.7895 \cdot dc \cdot hc + 1.87746 \cdot h^2 - 35.3771 \cdot hc^2$	5	0.862554	0.413491
Platanus hispanica	$B = 3.3003 - 0.500268 \cdot dc^2 + 0.270102 \cdot dc \cdot dbh$	5	-0.54426	0.601098
Sophora japonica	$B = 11.3625 - 0.871214 \cdot hc \cdot h + 0.213012 \cdot hc \cdot dbh + 0.168353 \cdot h^2 + 0.0274955 \cdot hc \cdot h \cdot dc$	5	-0.414982	0.689061
Phoenix canariensis	$B = -483.752 + 145.266 \cdot dc - 36.1174 \cdot h + 56.9057 \cdot hc - 0.395022 \cdot dbh \cdot dc + 0.840297 \cdot dbh \cdot h - 0.896813 \cdot dbh \cdot hc - 4.74705 dc^2 - 6.50947 \cdot dc \cdot h + 8.45532 \cdot h \cdot hc - 8.75568 \cdot hc^2$	5	-0.44431	0.668529
Phoenix dactilifera	$B = 64.4552 - 19.651 \cdot h + 20.2859 \cdot hc + 1.70061 h^2 - 2.08599 \cdot h \cdot hc$	5	0.391497	0.705651
Morus alba	$V = -591.746 + 507.093 \cdot do^2 - 2.09281 \cdot do^2 \cdot l + 0.0083961 \cdot do \cdot l^2$	5	-0.092665	0.928448
Morus alba	$B = 2.65673 + 0.573367 \cdot V$ cone	5	-0.247364	0.810857
Morus alba	$B = 2.65673 + 0.382245 \cdot V$ paraboloid	5	0.247367	0.810855
Platanus hispanica	$B = 6.10934 + 0.0992547 \cdot$ Vcone	5	-0.694087	0.507279
Platanus hispanica	$B = 6.10934 + 0.0661698 \cdot$ Vparaboloid	5	-0.694087	0.507279
Platanus hispanica	$V = -11.2731 + 0.620237 \cdot do^2 \cdot l$	5	0.0613361	0.952596
Sophora japonica	$V = 23.6538 + 0.313124 \cdot do^2 \cdot l$	5	0.068944	0.946726

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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 these resources is conditioned, by the amount of existing biomass within urban community ecosystems. This research was focused on direct and indirect quantification of lignocellulosic waste from urban tree pruning. The treated species, *Morus alba, Platanus hispanica, Sophora japonica, Phoenix canariensis* and *Phoenix dactilifera* are widely deployed as ornamental vegetation in Mediterranean countries. Mathematical models for predicting the available amount of pruning residues for each species were developed from easily measurable dendrometric parameters, such as diameter at breast height, crown diameter, total tree height, obtaining coefficients of determination between 0.67 and 0.96. These models can be used for urban inventories and the application of logistic models. On the other hand, Terrestrial Laser Scanner (TLS) technology was applied to improve the estimates of tree architectural parameters obtained by ground-level observations at individual tree level. For this, apparent crown volume was calculated by 4 different methods: *global convex hull* for the entire point cloud that forms the crown; *convex hull by layers* of 5cm height in the XY plane; triangulation by XY flat *sections*, and discretization of the point cloud in small elements of volume (*voxel*). Finally, residual biomass for each species was classified and characterized according to the UNE norms, including dimensional analysis of the obtained materials, density, moisture content, calorific value as well as carbon, nitrogen, hydrogen, and sulfur content. Models to predict the gross calorific value from the elemental composition were developed for fast indirect determination in industry.

RESUMEN

Una gran cantidad de biomasa residual con posible uso energético e industrial puede ser extraída de las operaciones de gestión de los árboles ornamentales de las ciudades. La rentabilidad del aprovechamiento de estos recursos está condicionada por la cantidad de biomasa existente en los ecosistemas urbanos. Esta investigación se ha centrado en la cuantificación directa e indirecta de los residuos biomásicos de la poda de árboles urbanos ornamentales. Las especies estudiadas fueron *Morus alba*, *Platanus hispanica*, *Sophora japonica*, *Phoenix canariensis* y *Phoenix dactilifera* las cuales son ampliamente utilizadas como vegetación ornamental en los países mediterráneos. Modelos matemáticos para la predicción de la cantidad residuos de poda disponible han sido desarrollados para cada especie a partir de parámetros dendrométricos de fácil medición, tales como diámetro del tallo a altura del pecho, diámetro de copa o altura total, resultando coeficientes de determinación entre 0.67 y 0.96. Estas ecuaciones pueden ser utilizadas para los inventarios urbanos y la aplicación de los modelos logísticos. Por otra parte, se han analizado técnicas de escaneado con láser terrestre (TLS) para mejorar las estimaciones de los parámetros dedrométricos de árboles existentes, y relacionarlos también con esta biomasa residual obtenida. Para ello se han calculado los volúmenes aparentes de la copa con 4 métodos diferentes: *global convex hull* para la nube de puntos que forma toda la copa, *convex hull por capas* de 5cm de altura en el plano XY, triangulación por secciones planas XY y discretización de la nube de puntos en los pequeños elementos de volumen (voxel). Finalmente, la biomasa residual de cada especie fue clasificada y caracterizada de acuerdo con las normas UNE incluyendo análisis de las dimensiones de los materiales obtenidos, densidad, humedad, poder calorífico, contenido de carbono, nitrógeno, hidrógeno y azufre. Modelos para la predicción del poder calorífico superior a partir de la composición elemental han sido desarrollados, para su determinación rápida en la industria de forma indirecta.

RESUM

Una gran quantitat de biomassa residual amb possible ús energètic i industrial pot ser extreta de les operacions de gestió dels arbres ornamentals de les ciutats. La rendibilitat de l'aprofitament d'estos recursos està condicionada per la quantitat de biomassa existent en els ecosistemes urbans. Esta investigació s'ha centrat en la quantificació directa i indirecta dels residus biomásics de la poda d'arbres urbans ornamentals. Les espècies estudiades van ser *Morus alba, Platanus hispanica, Sophora japonica, Phoenix canariensis* i *Phoenix dactilifera,* les quals són les àmpliament utilitzades com a vegetació ornamental en els països mediterranis. Models matemàtics per a la predicció de la quantitat disponible de residus poda han sigut desenrotllats per a cada espècie a partir de paràmetres dendromètrics de facil medició, tales com el diàmetre de la tija a l'alçada del pit, diàmetre de copa o alçada total de la planta, resultant coeficients de determinació entre 0.67 i 0.96. Estes ecuacions poden ser emprades per l'elaboració d'inventaris urbans i l'aplicació de models logístics. Per altra banda, s'han analitzat tècniques d'escanetjat amb làser terrestre (TLS) per mijorar les estimacions dels paràmetres dedromètrics d'arbres existents, i relacionar-los també amb esta biomasa residual obtinguda. Per allò s'han calculat els volums aparents de la copa amb 4 mètodes diferents: *global convex hull* per al núvol de punts que forma tota la copa, *convex hull* per capes de 10 cm d'alçada en el pla XY, triangulació per seccions planes XY i discretización del núvol de punts en els xicotets elements de volum (voxel). Finalment, la biomassa residual de cada especie va ser clasificada i caracteritzada d'acord amb la norma UNE incloent analisis de les dimensions dels materials obtiguts, densitat, humetat, poder calorífic, contingut de carbó, nitrógen, hidrógen i sofre. Models per la predicció del poder calorífic superior a partir de la composició elemental ha sigut desenvolupada, per la seua determinació ràpida en la industria de forma indirecta.

NOMENCLATURE

Symbol	Unit
mm	millimetre
cm	centimetre
m	meter
g	gram
kg	kilogram
cal	calorie
%	percentage

Symbol	Meaning
ALS	Airborne Laser Scanning
B	dry biomass (kg)
ba	bark (%)
C	Carbon (%)
ch	crown height (m)
CHM	digital crown height models
D	wood density (g/cm^3)
dbh	diameter at breast height (cm)
dc	crown diameter (m)
dl	large end diameter at the lower end of a section (cm)
dm	diameter midway along a section (cm)
do	base diameter of a branch (cm)
dob	diameter over bark (mm)
DSM	digital surface models
DTM	digital terrain models
du	small end diameter at the upper end of a section (cm)
dub	diameter under bark (mm)
f	form factor
GCV	gross calorific value (kJ/kg)
H	Hydrogen (%)
hc	distance from soil to the crown (m)
h	total tree height (m)
h_s	separation between sections (cm)
K	proportional factor between the paraboloid volume and hemisphere
l	length of a branch (cm)
ls	length of a section (cm)
LAI	leaf area index
LIDAR	Light Detection and Ranging
MAE	mean absolute error
M_{ar}	moisture content of biofuel (%)
m_1	mass of empty drying container (g)
m_2	mass of drying container and sample before drying (g)
m_3	mass of drying container and sample after drying (g)
m_4	mass of packaging moisture (g)
N	Nitrogen (%)
R^2	coefficient of determination
S1, S2	areas of the consecutive sections
S	Sulfur (%)
sd	standard deviation
sdf	standard deviation of form factor
TLS	Terrestrial Laser Scanning
V	volume of a branch (cm^3)
V_c	volume of a section (cm^3)
Vg	green volume (cm^3)
VLIM	Voxel-based Light Interception Model
VLS	vehicle-based laser scanning
Vgs	volume of a geometrical solid of same diameter and height (cm^3)
V_r	real volume of a section (cm^3)
v_m	model volume (cm^3)
vc	apparent crown volume (m^3)

W	oven-dried weight of wood (g)
W 10	up to 10% moisture content in wet basis (%)
X	coordinate
X_m	coordinate of the centre of the trunk
X_{min}	minimum value of X coordinate in the X plane
X_{max}	maximum value of X coordinate in the X plane
X_{pc}	coordinated of each point in the X plane
Y	coordinate
Y_m	coordinate of the centre of the trunk
Y_{min}	minimum value of Y coordinate in the Y plane
Y_{max}	maximum value of Y coordinate in the Y plane
Y_{pc}	coordinated of each point in the Y plane
Z	coordinate
Z_{min}	minimum value of Z coordinate in the Z plane
Z_{max}	maximum value of Z coordinate in the Z plane
ρ	distance from center of the trunk to a scanned point in the plant

1. INTRODUCTION

It is known that vegetation of urban, leisure, industrial and communication areas plays significant ecological, scenic and aesthetic functions, contributing to improving the quality of life in the urban surrounding. While urban vegetation was used primarily as a tool for ornamental purposes, it is important nowadays to focus on its role in environmental improvement. Few studies have estimated the impact of urban forest wood on environmental quality, among others the amount of residual biomass, which can be used to achieve ecological and energy targets. Due to routine care of urban greenery and planned changes in spatial structure of green areas within urban community ecosystems, waste is produced in form of woody parts that are an annually renewable resource.

It is estimated that urban tree wood originating from pruning operations is a potentially abundant, underutilized source of biomass that could contribute significantly more to regional and national bio-economies than it does at present. More effective utilization of wood residuals from urban areas, could offer bio-based fuels for heat and power generation, reduce pressure on forests, decrease waste disposal costs and land take up on a local and regional level (MacFarlane, 2009). The volume of generated lignocellulosic waste varies greatly, depending on the species, type and frequency of pruning practice, and other factors (Saiz de Omeñaca et al., 2004). Generally, the availability and characteristics of urban tree biomass, relationships between tree parameters and quantity of material yielded during management operations are not well documented.

Currently, municipalities are forced to destiny a relevant percentage of their budgets for the maintenance of urban green space. Nevertheless, only a minor share of woody residuals is being recovered. Few processes are applied to generate income that can offset the expenses of this operation (McKeever et. al, 2003, USDA, 2002). A great share of urban wood ends up in landfills (MacFarlane, 2007). Some woody residuals are recovered for composting, recycling or other uses (McKeever et. al, 2003). Moreover, the lack of precise information on the basic characteristics of species in relation with potential biomass is a barrier to the rational use of this material and the achievement of social benefits. Due to the above, there is a high necessity to create a comprehensive database on residual biomass from urban trees, which would enable to create and implement solutions that are both economically and environmentally attractive. To popularize the use of biomass from ornamental trees, to reduce maintenance outages in urban and recreation areas, it is necessary to specify the amount and characteristics of the material obtained.

In the urban zones, the development conditions of vegetation vary significantly from those that can be found in rural and forest areas. Due to the existence of buildings and pavement, solar irradiation, wind speed, air humidity and shading, a specific urban microclimate is generated, simultaneously influencing parameters such as the rate of growth and crown shape. Numerous studies have analyzed the costs, benefits and carbon storage capacity of urban forests. Nevertheless, these studies are limited by the lack of research on urban tree residual biomass. Moreover, the estimates of carbon storage in urban environments mainly rely upon allometric relationships developed for trees in traditional forests (McPherson et al., 2001, Pataki et al., 2006). More exact quantification of urban wood biomass depends on development of allometric relationships especially for urban trees. Reasons exist to believe, that allometry associated with traditional forests does not accurately represent urban systems. Characteristics such as low tree density in urban environments, connected with the potential competition for resources are one important point (McHale et al., 2009). Growing in an open environment, urban forests frequently receive additional water and nutrient supply. In North America, studies have shown, that urban trees, including those located in areas considered as stressful, noted higher rates of trunk growth comparing to published rates for the same species in traditional forests. It is concluded that this fact is due to a possible result of release from competition and above average precipitation (Rhoades et al., 1999). Trees in urban settings have different challenges comparing to those located in traditional forests such as damage, disease and pruning. The results indicate that soil moisture, air temperature, relative humidity, leaf temperature and vapour pressure deficit were less favourable for urban trees.

Direct tree biomass measurement by felling is accurate but time-consuming, expensive and forbidden in many environments. For this, destructive sampling is substituted with every time more adequate, indirect methods. Plant structure investigation is now focused on the possibility of replacing ground-level labor-intensive inventory practices with modern remote sensing systems. 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. This technology can be a new observational tool for precise characterization of vegetation architecture within natural and plantation-like environments. Introduced for applications in urban forests, allows three-dimensional modelling and geometrical characterization of trees, making it easier to develop management systems based on precise information.

The objective of this research was to study the possibility of using lignocellulosic residual biomass from urban forests, particularly as a renewable energy source or raw material for industry. For this, the study was focused on: direct biomass quantification removed under specific pruning operations; development of lignocellulosic biomass prediction models based on allometric relationships between tree dimensions and yielded biomass; development of methods of TLS point cloud processing to determine tree architecture; residual biomass estimation by TLS and ground observations; comparison of tree dimensions and crown volumes obtained with both methodologies; characterization of physical and chemical properties of materials for energy and industrial applications.

2. LITERATURE REVIEW

Urban forestry is defined as "*the art, science and technology of managing trees and forest resources in and around urban community ecosystems for the physiological, sociological, economic and aesthetic benefits trees provide society*" (Helms, 1998). Pruning is a horticultural practice that involves selective removal of undesired, diseased, damaged, dead or structurally unsound plant parts. Reasons to prune urban trees include deadwood removal, shaping, improving or maintaining health, reducing risk from falling branches or aesthetics (Galan Vivas et al., 2011). Clark et al., (2010) calls pruning the heart of arboriculture and one of the most important services that arborists provide. As pruning is a wounding process, that causes a certain level of injury to trees, it is important to limit it to the amount, which is necessary to accomplish the pruning objective. Correct pruning, can extend the life of urban trees, improve their safety and increase their value. On the other hand, improper pruning can damage a tree, decrease its value and make it hazardous. As pruning is also one of the most visible management actions provided on trees in the urban environment, it is important to make it a wise investment.

2.1. CHARACTERIZATION OF PRUNING CONDITIONS AND TECHNIQUES IN URBAN FORESTS

Gil-Albert (2001) describes five main conditions why trees should be pruned namely: technical conditions, aesthetic and landscape conditions, urban conditions, sanitary conditions and safety conditions. These are described below:

2.1.1. Technical conditions

According to which are the goals of pruning operations, these can be classified into:

a) Cleaning technique of pruning

Cleaning techniques of pruning, involve all types of pruning operations, where the main objective is to eliminate undesirable elements such as: hazardous, dead, dry, damaged or insect-infested branches and parts of trees, misdirected or crossed branches, branches located too close to each other or to the tree trunk. Also selectively are removed some epicormic branches, leaving those which demonstrate good development in desired directions. This leads to an increased airflow and development of a strong tree structure, as well as helps to eliminate conditions, that could cause risk to people and properties. These types of operations are necessary for all trees, for any age, species, location or dimensions (Gil-Albert, 2001).

b) Formation technique of pruning

Formation techniques of pruning, are all types of pruning operations, whose goal is to give a tree a certain shape, form. Unless man intervenes, trees according to their habitat and vegetative characteristics, adopt an aspect that is called natural. This can be variable. The most representative are globular forms, pyramidal or lobed. While the asymmetrical forms or parasol-shaped are more frequently evolved by human. The formation technique of pruning mainly focuses on the formation of the trunk, axis, skeletal branches and election of trunk height (Gil-Albert, 2001).

c) Maintenance technique of pruning

Maintenance techniques of pruning are all pruning operations, held in order to maintain the tree in good conditions for long periods of time (Gil-Albert, 2001).

d) Renewal technique of pruning

Renewal techniques of pruning, are operations by which undesired parts and elements of a tree, are removed in order to replace them with new and younger ones (Gil-Albert, 2001). This type of pruning is performed to improve the appearance, form and structure of trees that have been damaged, vandalized or pruned in a drastic way like topping. Restoring a tree usually requires a number of pruning interventions over a period of years.

Frequently formation techniques of pruning are identified with young trees, maintenance techniques with adult trees and renewal techniques with old trees (Gil-Albert, 2001).

2.1.2. Aesthetic and landscape conditions

When the tree is left to grow freely, it naturally takes a form characteristic of the species. However, man is able to guide its development and obtain a completely different shape, do to pruning and regular maintenance. The main objectives of pruning when taking to account aesthetic and landscape conditions are:

- A simple regulation of the natural shape of a tree,
- A set of formation and maintenance pruning techniques, in order to obtain artificial shapes (Michau, 1987).

A simple regulation of tree shape, such as formation of tree form, crown dimensions, the appearance and height of tree trunk, total tree height and tree density, allows gaining perspective and transparency.

When pruned according to specific geometric shapes, trees are involved in creating a certain landscape, hiding undesirable and unaesthetic views (Drenou, 2006, Gil-Albert, 2001).

2.1.3. **Urban conditions**

The urban green space, including tree-lined streets and avenues, as well as public parks, faces many limitations. First and most important, is the available space. The proximity of houses and narrow sidewalks often makes the tree exceed the desired space. The consequences of lack of space in some situations, may lead to lack of aeration and lighting. Moreover, the proximity of trees to windows and balconies provokes miner visibility and increased sensibility to vandalism and theft. Other limitation is the total height of urban tress. Very tall trees interfere with electrical networks and are more sensible to wind, what increases the risk of falling branches. Other reason leading to pruning operations are the visibility of traffic lights, street lamps and traffic signs, which cannot be covered by vegetation. Vehicle traffic mainly in case of buses and large trucks is another factor that requires certain trunk height and level of branches (Gil-Albert, 2001).

2.1.4. **Sanitary conditions**

Pruning can sometimes fight specific diseases or pests.

2.1.5. **Safety conditions**

The public nature of urban forests including roads, the presence of property and goods placed under the trees, as well as the traffic density, impose on the responsible institutions to guarantee satisfactory safety conditions for all involved users. For this, dead, damages and hazardous branches and other parts of the trees, must be removed regularly, to reduce injury or property damage risk (Drenou, 2006, Gil-Albert, 2001).

2.1.6. **Pruning palm trees**

Palm trees have a different anatomy and form than broadleaf evergreen, conifers and deciduous species. For this reason, they require special pruning. Basically, only dead fronds should be removed, while the elimination of live fronds should be limited to those that are severely chlorotic or broken. Moreover, palm fruit, flowers and loose petiole base should be removed, if considered to be a safety risk (ANSI A300, 2001). From a biological point of view, it is not convenient to prune palm trees, as the fronds contribute to better protection against cold, wind and salt. Mature fronds feed the fruit, new fronds and roots. Cutting vigorous green fronds, not only reduces the photosynthetic capacity of the plant and with it, the force of the tree and the capacity of producing young fronds, but also produces an unnecessary mobilization of reserves stored in the palm stipe (Del Cañizo, 2002). For this, their removal is very harmful. The motivations of pruning palms are essentially aesthetic, cultural and for safety reasons. Correct pruning of palm species should consist of keeping the highest number of live fronds. This allows protecting the terminal bud at the apex of the stipe, retaining a maximum amount of reserves, and mechanically supporting the young fronds (Drenou, 2006). When pruning palm trees, it is important not to use using climbing spurs (also known as hooks, spurs, spikes, climbers), in order to avoid wounds on the stipe and the spread of *Fusarium oxysporum* (Del Cañizo, 2002). It is also important, to disinfect pruning tools before and after pruning, in order to avoid transmitting disease-causing organisms on tools (ANSI A300, 2001).

2.2. URBAN FOREST BIOMASS ESTIMATES

Urbanization is increasing, and has the potential to increase in a greater scale in the years ahead. Many areas, with rapid urban expansion, are altering and displacing forests, agricultural areas and other value open spaces. As urbanization of landscapes increases, so does the importance of urban forests, their impact on local, regional and global environments and influence on great majority of population (Nowak et al., 2005). Planning and managing forests in and near urban areas, has been most affected by the urbanization process (Konijnendijk, 2000). Urban tree and woody yard residuals form an important component of the municipal solid waste stream. Some woody residuals are recovered for composting, recycling and other uses. Nevertheless, a significant amount is discarded. It is estimated that the total amount of tree and woody yard residuals, form a resource, as large as the timber harvest in National Forests in the United States. Both sources are not interchangeable, as the urban residuals are suitable for low value products such as mulch, while forest timber for high value solid wood and pulp products (McKeever et al., 2003).

Urban biomass research is commonly conducted at coarse scales that include entire cities and regions. There is lack of focus on individual tree biomass (McHale et al., 2009). Jenkins et al., (2004) observes that estimates of dry weight biomass of trees and particular tree parts are of great interest to managers, policymakers and researchers. A research by Pillsbury et al, (1998), notes that the urban forest inventories should describe composition, structure and volume of urban trees. For this, data should be collected on tree parameters, such as diameter at breast height and total tree height in addition to species location, health or damage rating. McFarlane (2007) notes, that wood biomass from urban zones is an extensive, rather than intensive resource, although land clearing and destructive weather events can lead to an increased amount in short periods of time. The research also points out, that the logistics of collecting and utilizing residual biomass is incomparable with harvesting from point sources such as plantations (McFarlane, 2009).

The concept „urban forest'' is defined differently across countries what makes it difficult to operationalise for the purpose of resource inventories (Konijnendijk, 2003). FAO (2002) reports, that „trees outside forests'' need to be uniformly described for better integrated and sustainable management. Following Konijnendijk et al., (2005), the characterization and assessment of urban forests in European cities and towns is a complicated task as few data exist or have been published and no comprehensive inventory seems to be available at the moment. Information on urban green space cover in Europe has been based on few surveys, varies depending on author and includes assessment for only selected European cities. The European Environment Agency (EEA) (1995) estimates the urban forest surface within municipal boundaries between 5% (Madrid) and 60% (Bratislava), while Pauleit et al. (2002) at the level from 1.5% (Thessaloniki) up to 62% (Ljubljana). Ottitsch (2002) points out an average of approximately 30% (5%-56%) or 6-7000 m^2/inhabitant of green space for 14 surveyed European cities. In a research by Konijnendijk (2001), average woodland cover within municipal boundaries of 26 larger European cities is estimated at 18.5% (104 m^2/inhabitant). Spain is estimated to have between 0.8 m^2/inhabitant (Pamplona) and 39.2 m^2/inhabitant (Vitoria-Gasteiz) with an average of 8.95 m^2/inhabitant, respectively (Observatorio de la Sostenibilidad en España, OSE, 2009). In 2012 the population of EU-27 reached 503.5 million people of which in Spain 46.2 million people (Esurostat, 2012). This would give a number of 413.5 million m^2 of urban green areas in Spain and 52364 million m^2 in Europe. The city of Valencia has an approximate surface of 4.6 million m^2 of green areas that can be exploited as a source of biomass generated in the pruning and maintenance of plant species (Urribarrena, 2011). This biomass is calculated at the level of 4518 tones/year (OAM, 2012) of mixed material or 0.98 kg/m^2 year. Other research (Siuta, 2000), reports 5 t/ha year of green mass in Poland. In a study held in Oklahoma, USA, biomass dry matter yields of urban green waste are quantified as: lawn detaching between 4245-7220 kg/ha, lawn mowing 125-765 kg/ha, tree pruning (mulberry) 1905-2520 kg/ha and leaf raking (mulberry) 305-1640 kg/ha, respectively. The calculated quantity was dependent on annual precipitation and month of maintenance operations (Springer, 2012). All authors express concern about data comparability and quality, issuing problems as different green space categories and lack of record and inventories of urban tree resources (Konijnendijk, 2003). Lack of data at national and international level has also been a result of different levels of planning and management hierarchy as well as variety of owner structures. On the other hand, a number of examples of well developed inventory and management systems exist in larger cities. However, even those rarely include private and commercial spaces that present a significant proportion of urban tree population. There is also little data on composition and characteristics of urban forests. A survey by Pauleit et al. (2005) show, that green space cover varies significantly across the countries. European Environment Agency (EEA) (2010) demonstrates a lower share of urban green space in the south and west of the continent. Besides quantitative differences, Pauleit et al. (2005) observe differences in species composition depending not only on climatic zones but also local planting policies. This research demonstrates, that Northern-European cities have lower diversity of species due to harsh climatic conditions comparing to Central and Western Europe. In the last, despite a broad selection of species, at least 50% of street trees represent three to five genera. Other research proves that parks, gardens and road alignments of the cities are characterized by a large number of different species, what makes it complicated to quantify the potential energy value for Spain and Europe. In case of Valencia are found 214 different species of trees (Samo Lumbreras et al. 2001).

Care, maintenance and renovation of green spaces requires removing grass, foliage of trees and shrubs, branches, entire trees and shrubs, harvest from vines and hedges, herbaceous and waterside vegetation, all at different stages of vegetation, various moisture content and some partly decomposed. The quantity of removed biomass is proportional to the health and growth intensity of vegetation and depends mostly on soil fertility, irrigation, climatic conditions and frequency of maintenance operations. Systematic removal of organic material from urban green areas decreases soil fertility and eventually its productivity (Siuta, 2000, OAM, 2012). Depending on country, these looses are compensated by use of external origin compost and mineral fertilization (Siuta, 2000) or by mulching extracted biomass and leaving it *in situ* (OAM, 2012). In most cases, plant mass is treated as one stream, loaded into containers and transported to landfills. Only in some cases it is used for composting, biogas production, fertilization or solid biofuel production such as pellets and briquettes. Pruning is held to maintain the highest standing biomass and only remove dangerous or damaged parts, what makes it impossible to estimate a mean weight of concrete materials, and energy value specific to the material. Due to differences in biomass treatment, management policies, environmental awareness, accessible technology and economical background, the quantity of plant mass removed under pruning will significantly vary on local, national and international level. Best information will be held by greenery companies, waste management companies and landfills. A research by Blokhina et al. (2011) argues, that landscape management grass is mostly harvested late, resulting in unfavourable composition for many utilization purposes. However, biogas production can be a sensible option for using landscape management grass, while the harvesting period is of extraordinary importance as it affects methane yield. Grass is described as a highly inhomogeneous material with extremely variable substrate characteristics (Prochnow et al., 2009). It has been verified, that methane yields decrease with advancing stage of vegetation (Prochnow et al., 2005). This is a result of increasing contents of crude fibre that decreases the maximum biogas production potential, as crude fibre consists mainly of hemicellulose and lignin, both hardly degradable under anaerobic conditions (Prochnow et al., 2005). The biogas yield from fresh green grass is estimated at 520-640 m^3/t VS (El Bassam, 1998). Agricultural and forest residuals can be used for biofuel pellet production. Although the chemical constituents and moisture content of biomass materials vary, due to low amounts of polluting elements and ash (Heschel et al., 1999, Gil et al., 2010) the production of pellets prepared with biomass is becoming a more attractive source of energy (Larsson et al., 2008). The combustion processes of biomass materials are complicated due to highly complex chemical and physical composition, moisture content, density and heterogeneity of these materials. Other disadvantage is the low mechanical resistance of material what leads to high dust emissions, and an increased risk of fire and explosions during pellet handling, storage and transport (Temmerman et al., 2006). Although the combustion characteristics of biomass may vary depending on the composition of the raw material, the use of biomass/coal blends could produce fuel pellets with more suitable characteristics for combustion as coal has a higher carbon content and calorific value in comparison to biomass (Heschel et al., 1999). Few studies have compared different types of biomass for pellet fabrication, taking as main raw material wood residues. Furthermore, the heterogeneity of the raw materials used in pellet and briquette production makes it difficult to estimate their calorific potential. Pellet obtained from residuals proceeding from pruning of fruit species is estimated to have net calorific value 3800-4500 kcal/kg (Fernandez Gonzalez, 2010). The net calorific value of road side green is estimated as 14,1 MJ/kg (FAO, 2004). Gillon et al., (1997), determined the mean calorific values of green twigs, stalks and leaves for 14 broad-leaved species (18.80-21.10 MJ/kg), 5 conifer species (20.29-22.56 MJ/kg) 24 shrub species (18.65-24.59 MJ/kg) 6 grass species (17.05-18.89 MJ/kg), respectively. Castells (2005) reported net calorific value of park residuals and wood slightly above 4000 kcal/kg. *Morus alba* is characterized as medium-quality fuel wood with a calorific value of 4370-4770 kcal/kg (World Agroforestry Center, 2012). To compare, the gross calorific values of most common fuels are: carbon 34080 kJ/kg, coal 15000-27000 kJ/kg, petrol 48000 kJ/kg and vegetable oils 39000-48000 kJ/kg. A research held by Siuta (2000) described the nutrient content in urban green cover organic material (foliage, herbaceous plants, wood chips, twigs, branches, waterside vegetation) in the city of Warsaw at following levels: zinc 22-260 mg/kg dry mass, cadmium 0.1- 0.3 mg/kg dry mass, lead 0,7-25,0 mg/kg dry mass, chromium 1.0-12.0 mg/kg dry mass, copper 1.3-22.7 mg/kg dry mass, respectively. These contents will be city specific and depend on degree of pollution. Garden plants were characterized with 2.34% ash, while dry leaves 3.83% ash (Castells, 2005).

The EU-27 energy production by source in 2009 was the following: 28,4% nuclear, 20,4% solid fuels, 18,8% natural gas, 12,8% crude oil, 18,3% renewable energy (Eurostat, 2012). While within the primary production of renewable energy in 2009, biomass and waste were at the level of 67.7% in EU-27 and 47.9% in Spain (Eurostat, 2012). The percentage of biomass proceeding from pruning operations is not specified. Nevertheless, biomass is the leading source of renewable energies in EU-27 and green spaces residuals could play a significant role in the future.

Numerous studies have analyzed carbon storage capacity, physical and biological costs and benefits of urban vegetation, improvement of air quality, pollution reduction, energy conservation, noise reduction, effects on ozone and hydrology, as well as social and economic benefits related with urban trees (Akbari, 2002, McHale et al., 2009, Johnson et al., 2003, Nowak et al., 2007). These studies have been limited by lack of research on urban tree biomass (McHale et al., 2009) and direct measurement of urban tree volume (McPherson et al., 2001, Pataki et al., 2006). In most research, urban tree wood biomass estimates were done for whole aboveground biomass, using models for forest-grown softwoods and hardwoods. Forest-derived biomass equations overestimate biomass from urban species (Nowak, 1994). Equations used in biomass prediction normally use parameters such as diameter at breast height, tree height and crown dimensions to yield all aboveground biomass estimates. In general, research conducted on urban settings has been limited (Peper et al., 1998). Variables that affect tree growth as site characteristics (soil, water etc.) and climatic conditions are different among cities, what causes that allometric relationships will vary (McHale et al., 2009 Eamus et al., 2000, Kuyah et al., 2012). Management practices also influence biomass production and allocation within trees in landscape (Keith et al., 2000, Ong and Huxley, 1996). Droppelman and Berlier, (2000) argue that pruning may affect the rate of biomass accumulation as cutting and pruning can change biomass without changing dbh. For that, allometric equations based on dbh should be refined by including height, wood density, or crown area to improve accuracy (Ketterings et al., 2001, Chave et al., 2005). At the moment, studies concentrated on developing methods for predicting and quantifying residual biomass proceeding from pruning operation of urban trees seem unavailable or not published. However, data on characterization of particular tree parts have been reported. Information on total leaf-surface area and leaf dry-weight biomass for open grown urban trees have been based on equations derived from diameter at breast height and crown parameters such as crown height, average crown diameter and average shading factor for individual species (Gacka-Grzesikiewicz, 1980, Nowak, 1996). These studies found, that estimates based on crown width gave lower mean square errors comparing to models based on diameter at breast height. Nevertheless, these data have been obtained for healthy, full-crown open-growing delicious trees and will tend to overestimate leaf area and biomass in cases as pruning (Gacka-Grzesikiewicz, 1980, Nowak, 1996). Other studies estimate crown biomass and leaf area from allometric equations based on sapwood area, diameter at breast height and crown dimensions (McPherson 1998, Turner et al., 2000, McHale et al. 2009, Dobbs et al., 2011). Crown biomass calculations have been based on non-destructive methods as randomized branch sampling, while leaf area on direct methods as foliage and litter fall collection, leaf area index and destructive sapwood measurement (Turner et al., 2000, Dobbs et al., 2011). Dobbs et al., (2011) developed branch biomass equations with R^2 from 0.4 to above 0.6 noting, that some of the equations overestimate biomass in smaller trees. This might be a result of faster height growth rates comparing to diameter-growth rates in juvenile trees affecting the diameter-height relation. Peper et al., (1998) listed other indirect methods as the use of aerial imagery and video images.

As a potentially new line of investigation, no commercial or technical equipment for pruned biomass estimation has been found in previous studies.

A study by McHale et al., (2009) incorporated a list with a number of equations derived from other studies, including only those, that represented a measure of all aboveground biomass without leaves and with a large enough diameter range for comparison purposes. The majority of mentioned equations were derived from trees growing in traditional forests and climates that differ from where the equations were applied (Table 1). One study by Pillsbury et al., (1998), developed volume equations for trees in urban environments. Total tree volume, including volume of all stem segments from ground level including terminal branches and bark was determined.

Table 1. Sources for allometric equations used in urban biomass studies (McHale et al., 2009)

Species	Equation	Source Species	DBH Range (cm)	Source
Bur Oak, *Quercus macrocarpa*	QU1	Red Oak	13–129	Brenneman et al. 1978, Ter-Mikaelian and Korzukhin 1997
	QU2	Bur Oak	3–40	Perala and Alban 1994
	QU3	Oak	14–163	Bunce 1968
Silver Maple, *Acer saccharinum*	ACS1	Sugar Maple	6–168	Young et al. 1980, Ter-Mikaelian and Korzukhin 1997
	ACS2	London Plane	15–74	Pillsbury et al. 1998
	ACS3	Silver Maple	5–46	Alemdag 1984
Green Ash, *Fraxinus pennsylvanica*	FR1	White Ash	13–129	Brenneman et al. 1978, Ter-Mikaelian and Korzukhin 1997
	FR2	Green Ash	15–84	Pillsbury et al. 1998
	FR3	Green Ash	3–79	Schlaegel 1984
	FR4	Ash	9–104	Bunce 1968
Honeylocust, *Gleditsia triacanthos*	GL1	General	10–85	Harris et al. 1973, Jenkins et al. 2004
	GL2	General	>94	Hahn 1984
	GL3	Green Ash	15–84	Pillsbury et al. 1998
Little Leaf Linden, *Tilia cordata*	TI1	American Basswood	13–129	Brenneman et al. 1978, Ter-Mikaelian and Korzukhin 1997
	TI2	American Basswood	5–56	Alemdag 1984
Populus sargentii	PO1	Cottonwood	6–32	Standish et al. 1985
	PO2	Cottonwood	>94	Hahn 1984
American Elm, *Ulmus americana*	ULA1	American Elm	5–30	Perala and Alban 1994, Ter-Mikaelian and Korzukhin 1997
	ULA2	General	10–85	Harris et al. 1973, Jenkins et al. 2004
	ULA3	Elm	>94	Hahn 1984
	ULA4	American Elm	5–56	Alemdag 1984
Hackberry, *Celtis occidentalis*	CE1	Hackberry	>94	Hahn 1984
Siberian Elm, *Ulmus pumila*	ULP1	General	10–85	Harris et al. 1973, Jenkins et al. 2004
	ULP2	Sawleaf Zelkova	6–34	Pillsbury et al. 1998
	ULP3	American Elm	5–30	Perala and Alban 1994, Ter-Mikaelian and Korzukhin 1997
	ULP4	Elm	>94	Hahn 1984
	ULP5	American Elm	5–56	Alemdag 1984
Kentucky Coffee Tree, *Gymnocladus dioicus*	GY1	General	10–85	Harris et al. 1973, Jenkins et al. 2004
	GY2	General	>94	Hahn 1984
Norway Maple, *Acer platanoides*	ACP1	Sugar Maple	6–168	Young et al. 1980, Ter-Mikaelian and Korzukhin 1997
	ACP2	Sugar Maple	3–66	Bickelhaupt et al. 1973, Tritton and Hornbeck 1982

2.3. METHODS TO DETERMINE THE ENERGY POTENTIAL OF BIOMASS

There are three standard methods to analyze energy potential of biomass namely elemental, proximal and structural analysis.

2.3.1. Elemental analysis

The elemental analysis is one of the most important factors when studying the properties of biofuels. The elemental composition of biomass is complex and contains six major organic elements and at least ten inorganic elements important for ash characterization as well as traces of heavy metals (Demirbas, 2003). With the analysis of the percentage of N (nitrogen), S (sulfur) and Cl (chlorine) can be assessed the impact of the use of biomass. While from the concentration of C (carbon), H (hydrogen) and N (nitrogen), can be determined the Heating Value (HV) of biomass.

The C and H are oxidized during combustion by exothermic reaction with the formation of CO_2 and H_2O (Obernberger et al., 2006). Carbon concentration has a positive relationship with Gross Heating Value (GHV) (Callejon et al, 2011, Telmo et al., 2010) justifying major GHV of wood than herbaceous biomass (Obernberger et al., 2006). Moreover, the incensement of the ratio of the sum of C and H in respect to O (oxygen) increases the GCV (Demirbas, 2002). The determination of these elements should be done in accordance with the UNE-CEN/TS 15104:2008. The concentration of C, H, and O in biomass is found in following ranges: 42-71%, 3-11% and 16-49% of mass (Vassilev et al., 2010). The analysis of the concentration of N in biomass is important for environmental protection due to emission of nitrogen oxides during combustion (Khan et al., 2009). Lower values of nitrogen in biomass are found in wood of conifers and deciduous trees comparing to crop residues (Obernberger et al., 2006). Normally the concentration of N in biomass ranges from 0.1 -12% of mass (Vassilev et al., 2010). The determination of N should be done in accordance with UNE-CEN/TS15104:2008. Biomass also contains low amounts of S estimated at 0.01-2.3% of mass (Khan et al., 2009). The determination of sulfur should be done in accordance with ASTM E775-87 (2008).

The main problem of Cl content in biomass is associated with hydrochloric acid frequently deposited on the metal parts of furnaces, stoves and boilers (Demirbas, 2005, Khan et al., 2009, Salmenoja et al., 2000). Its concentration varies for different types of biomass between 0.01 to 0.9%, tends to be scarce in wood and more abundant in straw, cereals and fruit residuals (Khan et al., 2009, Obernberger et al., 2006). The determination of Cl should be done in accordance with ASTM E776-87 (2009).

The ash content in biomass is essential for choosing proper combustion techniques. Wood biomass or horticulture residuals are characterized with low ash content (Callejon et al., 2011, Obernberger et al., 2006). The ash determination is done in accordance with UNE-CEN/TS 14775:2007.

2.3.2. **Proximal analysis**

Proximal analysis consists of the performance of necessary tests to obtain the contents of volatile organic compound (VC), fixed carbon (FC) and ash (Saidur et al., 2011, Khan et al., 2009). The study of these three parameters can be very important for understanding the phenomena of combustion of biomass as they are related to problems as ignition. Moreover, the heating value of biomass increases with higher FC and VC.

Ash is the inorganic and incombustible part that remains after complete combustion. The ash content varies between fuel types, species, plant parts and soil contamination. The available nutrients, soil quality, fertilizers and weather conditions influence the K (potassium), Na (sodium), Cl and P (phosphorus) content. Woody biomass usually is rich in Ca (calcium) and K, while herbaceous biomass often shows high levels of Si (silicon) (Saidur et al., 2011, Demirbas, 2005). The ash concentration in biomass varies from 1% in wood to 30-40% in vegetable waste. Generally, high concentrations of ash decrease the calorific value (Khan et al., 2009, Demirbas, 2004, Demirbas, 2002). The determination of ash should be done in accordance with UNE-CEN/TS 14775:2007.

Biomass usually contains a high content of volatiles. Because of high volatile fraction, biofuels can ignite even at low temperatures and the rapid loss of this fraction makes it necessary to maintain high temperature conditions in order to achieve complete combustion, ensuring efficient and low emission levels (Khan et al, 2009). The volatile organic compound content varies usually between 48-86% of mass in dry basis (Vassilev et al., 2010) and should be determined in accordance with UNE-CEN/TS 15148:2008.

The FC is obtained by calculating the difference between 100% and sum of percentage of mass of ash and VM in dry base (Telmo et al., 2010). This parameter is estimated between 1-38% of mass in dry base (Vassilev et al., 2010).

2.3.3. **Structural analysis**

Biomass contains a variable amount of cellulose, hemicellulose, lignin, a small quantity of lipids, proteins, sugars, water and inorganic constituents (Saidur et al., 2011, Demirbas, 2005). The first three are the most important. The hemicellulose, cellulose and lignin are called lignocellulose. The structural analysis of biomass is highly important to understand the combustion process and determination of GCV (Saidur et al., 2011). Cellulose and hemicellulose are abundant in hardwoods, while lignin is more abundant in softwood. A positive relation is reported between hemicellulose and lignin concentration and GCV (Demirbas, 2001, Demirbas, 2005).

The advantages and disadvantages between the described methods are mostly related to the complexity and necessary time to carry out an analysis.

2.4. LIDAR TECHNOLOGY

LIDAR technology (Light Detection and Ranging) is an active remote sensing system which emits energy that after colliding with objects, returns to the sensor, enabling to measure the distance of objects based on time interval between energy pulse emission and reflection after reaching the targets (round trip) (Moorthy et al., 2011). It enables to record massively information on a 3-dimensional scale from ground-level Terrestrial Laser Scanning (TLS) or Airborne Laser Scanning (ALS). The ALS can record the return signal of a pulse emitted at different echoes and with the help of a GPS and an inertial system, permits calculating the coordinates of the point, where there has been reflection, as well as its intensity (Baltsavias, 1999). The backscattered laser pulse from ALS systems, has been used to extract dimensional parameters such as crown dimensions (Means et al., 2000; Popescu et al., 2008), crown volume (Hinsley et al., 2002, Riaño et al., 2004) and tree height (Andersen et al., 2006; Morsdorf et al., 2004; Hopkinson, 2007; Yu et al., 2004). Also, it enables to define digital terrain models (DTM), digital surface models (DSM) and digital crown height models of vegetation (CHM) with applications for natural resource management (Hudak et al., 2009). It is also used in other multiple areas: geological, morphological and hydrological works, hydraulic modelling (Cobby et al., 2001), building representation (Sohn et. al, 2007), changes in beach sand (Shrestha et al., 2005), fire prediction models and management, as well as forestry applications (Lefsky et al., 1999, Naesset 2002; Maltamo et al., 2006, Popescu et al., 2007). Retrievals from ALS systems, have the advantage of capturing information over a large area, but their laser pulse return density (pts/m^2) is rather low (3-20 backscattered pulses/m^2) (Moorthy et al., 2011). This level of detail is many times insufficient to provide a detailed profile of the vertical axis of a tree crown and bottom parts of vegetation canopies.

Terrestrial LIDAR systems are based on the same principles as the ALS, while having differences in the way of operating. They provide a point cloud, a 3D digital representation of scanned vegetation, in which each point is characterized by an X, Y, and Z coordinate. It permits to work in local coordinates or in a specific reference system. From each station or viewpoint of the instrument, a model is generated, that can be linked to others by marks or homologous identifiable points. Scanning density can become very high, up to 1 point per millimetre. The TLS systems, allow the characterization of the vertical distribution of vegetation structure (Radtke et al., 2001), that could replace manual field inventory practices. These instruments are increasingly used in various applications, ranging from mining, industry, construction, civil engineering, documentation of accidents and criminal investigation, forestry and agricultural applications, etc. In the last field, the information from the TLS can provide a better definition of the structure of vegetation as with this system are obtained data from the whole plant, while the ALS system provides less data of the lower and lateral parts. Moreover, TLS systems have been used to estimate plant area densities (Takeda et al., 2008, Hosoi et al, 2006), ratios of woody to total plant areas (Clawges et al., 2007) and segmentation of tree stem diameters and branching structures (Henning et al., 2006, Hopkinson et al, 2004, Thies et al., 2004). A research by 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. This research claims that LIDAR-based methodologies give the possibility of replacing labour intensive inventory practices in forestry and agriculture. It presents TLS systems as potentially new observational tools for precise characterization of vegetation architecture.

It is possible to combine the information from TLS and ALS, getting data for the entire plant and area. This permits obtaining a good definition of the tree structure and correlating the parameters of the digital model with classic dendrometric data that require slow and laborious measurements (Hollaus et al., 2006).

Numerous studies relate dendrometric variables obtained with traditional instruments with important parameters used in the management of forests (Velázquez et al., 2010), such as pesticide dose optimization (Palacin et al., 2007), knowledge of growth rates and plant productivity (Lee et al., 2009), estimation of biomass of each tree and its use as a physical parameter to indicate tree health status (Lin et al., 2010) or the quantification of waste generated in pruning (Velazquez-Marti et al. 2011a, Velázquez-Martí et al., 2011b). Many studies of TLS data are directed towards obtaining geometric variables of tree crown height, width, surface area and volume (Tumbo et al., 2002, Lee et al., 2009, Moorthy et al., 2011). Some studies argue that ALS systems tend to underestimate total tree height, due to probability of missing tree tops even with high sampling densities (Popescu et al., 2002; Chen et al., 2006). The variable crown volume is one of the most interesting for the management of plantations. Many studies address the problem of crown volume calculation by several methods for different species of tree crops (Wei et al., 2004) and vineyards (Palacin et al., 2008, Rosell et al., 2009). In forest studies, the TLS was also conducted on modelling trees for their comparison with data obtained by airborne LIDAR or classical instrumentation (Kato et al., 2008), analysis of their structure (Gorte et al., 2004, Parker et al., 2004), both in large and homogeneous forest environments (Lovell et al., 2003), and in riparian areas, where equations of resistance to water flows were calculated (Antonarakis et al., 2009).

Some authors use three-dimensional matrix, where the smallest element of information is the voxel (Stoker, 2009). Processing models based on this concept, such as voxel-based Light Interception Model (VLIM) (Van der Zande et al., 2010), can estimate the percentage of incident sunlight that passes through the canopy and determines the LAI (leaf area index) in trees at different stages of leaf growth. With the K-dimensional tree algorithm, point clouds can be discretized in voxels, resampling the data at different resolutions (Park et al., 2010). This method shows several advantages such as

(Stoker, 2009): 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 the trees can be modelled if the laser signal penetrates enough into the tree crown from different stations. Other authors, focused on the division of the point cloud into horizontal or vertical sections, estimating the volumes of the solid within the different sections (Palacin et al., 2007). Moorthy et al., 2011, estimated the volume, deriving from these sections the radius of the circles with the same surface. The work of these authors is particularly noteworthy, given that they also use the convex hull algorithm applied to the flat sections of the point cloud. This algorithm, compared with Savitzky-Golay filter and the values derived from direct field data, is shown as one of the most accurate when studying the growth and productivity of plants (Lee et al., 2009).

Many studies, used laser instruments mounted on mobile platforms known as vehicle-based laser scanning (VLS) in tree crops. However, the accuracy of these equipments is not comparable with the fixed instruments (Lee et al., 2009). Small variations in the distance between the sensor and the tree, as well as the speed of the platform, with slight changes in the shape of the tree, produce errors above 9% in volume calculation. Lin et al., (2010), argues that the TLS is less efficient comparing to VLS, due to laborious recollections when surveying multi-plots of trees. This author claims, that biomass estimation at individual tree level will progress and become less money and time-consuming with VLS systems.

3. OBJECTIVES

3.1. MAIN OBJECTIVE

The aim of this research is to develop methods for indirect quantification of lignicellulosic residual biomass yielded from pruning operations of the mainest Mediterranean urban trees.

3.2. SPECIFIC OBJECTIVES

a) Direct quantification of residual lignocellulosic biomass coming from pruning operations of the following species of urban trees: *Morus Alba, , Phoenix canariensis, Phoenix dactilifera, Platanus hispanica, Sophora japonica*, which are the mainest in Mediterranean areas.

b) Development of lignocellulosic biomass prediction models based on allometric relationships between dendrometric parameters of the trees and quantity of residual biomass.

c) Development of methods of LIDAR data processing from terrestrial scaners to determine dendrometric parameters of the studied species.

d) Analysis between volumetric calculations obtained by terrestrial LIDAR technology and the residual wood biomass from pruning.

e) Characterization of physical and chemical properties of materials in order to evaluate their suitability for energy and industrial applications.

4. MATERIALS AND METHODS

The research presented in this paper is divided into three main blocks:

a) Direct quantification of biomass from pruning and development of mathematical prediction models based on allometric relationships between tree dimensions and quantity of yielded residual.

b) Development of calculation methods of tree architectural parameters and crown volumes extracted from a TLS point clouds. Inter-comparison of analyzed methodologies.

c) Characterization of biomass from an energetic and industrial point of view. Determination of models to predict the calorific value from the elemental composition for fast indirect determination in industry.

4.1. DENDROMETRIC ANALYSIS AND ALLOMETRIC EQUATIONS

The study area was located in the province of Valencia: Alcudia, Alzira, Mislata, Sagunto, Valencia. Taking Valencia as reference, the area is located in latitude 39°28`50`` and length 0°21`59``W. The average annual temperature is 17.8°C. Maximum temperatures are observed in August, with the average 25.5°C. Minimum average temperatures reach 11.5°C and are observed in January. Average annual rainfall is 454 mm and relative humidity 65%. The driest period is in July and the wettest in October (www.aemet.es). To perform this study, five ornamental species from the Mediterranean urban forests were selected namely: *Morus Alba*, *Phoenix canariensis*, *Phoenix dactilifera*, *Platanus hispanica, Sophora japonica*. The procedure of trial consisted of a random selection of municipal streets with dense car and pedestrian traffic and city parks and n =30 trees per species. Best effort was made, to obtain highest sample range possible. Within the studied species, each sampled group was randomly selected and is represented by widest size range possible to obtain in cooperation with maintenance companies. Previously to carrying out tree management operations, took place the identification of the selected sample trees. Field data sheets used in the trials are shown in the annex.

Following information was obtained during field research:

a) General information: species, variety, location and province. Moreover, contact data: name of the person in charge, address, telephone number and email. All information was collected in an interview with the person responsible for the management operations.

b) Tree management information: date and type of last pruning operations, tree identification number, diameter at breast height, crown diameter, distance from soil to the crown, total tree height and weight of pruned biomass. Information on date and type of last pruning operations were collected in an interview with the person responsible for the management operations. Trees were numbered sequentially, following the direction of traffic. Tree parameters were measured manually before pruning process started.

Diameter at breast height (dbh) outside bark was measured with a traditional aluminium caliper with precision 0.001 m in small trees or a diameter tape also with precision 0.001 m in big trees at a point 1.3 m above ground level on the uphill side. For trees with elliptical cross sections, the arithmetic average of the long and short diameters was used. Trees that were abnormally shaped, leaning, crooked or forked at or below breast height, were not included in the sample (Husch et al., 2003, West, 2009). The diameter at breast height was reported in cm.

Crown diameter (dc) was measured with a diameter tape with precision 0.001 m and a mirror. Determination of crown diameter at field was complicated due to the irregularity of the crown's outline. For this, the edges of the crown were projected to the ground and next was measured the length along the long and perpendicular axis from one edge point to the other edge point passing through the crown centre. The diameter was determined by averaging measurements of the long axis diameter 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.

Total tree height (h) 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 total height was measured from the base of the tree 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.

Distance from soil to the crown (hc) was determined with a Vertex IV hypsometer with precision 0.01 m. The height was measured from the base of the tree on the uphill side to the base of the tree crown. As a reference for identifying the base of the canopy, the halfway between the first and one or more live branches was taken. The distance from soil to the crown was reported in m (Dieguez Aranda et al., 2003).

Once pruning operations ended, the residual biomass was formed in bundles and weighted by means of a dynamometer with precision 0.01 kg (Figure 1). Weight measurements were carried out in field conditions. Samples of wood were put into small closed plastic containers in order to determine moisture content in laboratory conditions and obtain dry matter results. Where pruning operations were done in the presence of foliage, several branches of each sample-tree were manually defoliated, to determine the percentage of foliage and wood mass. Sample branches were collected for further volume calculations.

Figure 1. From left to right: bundles of pruned branches; weighting process with a dynamometer

4.1.1. **Dendrometric analysis of branches**

The dendrometric analysis is focused on developing methods, to easily calculate the actual volume of particular tree structures. For this, two approaches were carried out: morphic coefficient f (also called form factor) and volume functions were studied.

a) Morphic coefficient f is defined as the ratio between the actual volume and a geometric model volume taken as reference (Equation 1) (Husch et al., 2003). The models that provide the form factor most approximate to 1, best define the shape of the branch.

$$f = \frac{V}{Vgs} \qquad (1)$$

Where
f = form factor
V = volume of a branch (cm^3)
Vgs = volume of a geometrical solid of same diameter and height (cm^3)

The form factor allows determining the volume of any structure by measuring the basal diameter and length. In principle, the form factor should be a parameter characteristic of the species and diameter class. However, for each of the tests performed there is a statistical variability. For this, the mean and standard deviation for each of the cases were determined. The form factor can be influenced by the base diameter and length of the branch. This influence was analyzed.

Actual volume determination was carried out on sample branches collected after pruning operations. To calculate the actual volume, each branch was divided into equal sections with the length of 20cm (Figure 2). The large end, small end and midway diameters of each section were measured by means of a digital caliper with precision 0.01 mm. The volume of each section was calculated applying equations shown in Table 2 (Lopez Serrano et al., 2003; Velazquez et al., 2009; West, 2009). The volume of the whole branch was obtained by adding up all section volumes.

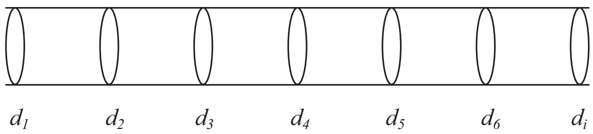


Figure 2. Measurements of diameters in each section

Table 2. Equations for volume of each branch section

Sectional Volume Formulae	Equation for Volume
Huber`s formula	$v_r = \frac{\pi}{4} \cdot dm^2 \cdot ls$
Smalian`s formula	$v_r = \frac{\pi}{8} \cdot (dl^2 + du^2) \cdot ls$
Newton`s formula	$v_r = \frac{\pi}{24} \cdot (dl^2 + du^2 + 4dm^2) \cdot ls$

v_r: real volume of a section (cm^3); dl: large end diameter at the lower end of a section (cm); du: small end diameter at the upper end of a section (cm); dm: diameter midway along a section (cm); ls: length of a section (cm)

Assuming the shape of a branch to resemble a solid of revolution (cone, cylinder, paraboloid and neiloid), the equations used to calculate the model volume of a branch are shown in Table 3 (Husch et al., 2003).

Table 3. Equations to compute volume of solids of revolution

Geometric solid	Equation for volume
Cylinder	$v_m = \frac{\pi \cdot d_o^2}{4} \cdot l$
Paraboloid	$v_m = \frac{1}{2} \frac{\pi \cdot d_o^2}{4} \cdot l$
Cone	$v_m = \frac{1}{3} \frac{\pi \cdot d_o^2}{4} \cdot l$
Neiloid	$v_m = \frac{1}{4} \frac{\pi \cdot d_o^2}{4} \cdot l$

v_m: model volume (cm^3); d_o: base diameter of a branch (cm); l: length of a branch (cm)

b) Regression models were analyzed in order to define volume functions, considering as dependent variable the total volume of the structure (V) and as independent variables the base diameter (d_o) and total length of the branch (l) (Table 4.)

Table 4. Branch volume functions

Author	Equation
Naslund (modif), (Naslund, 1940)	$V = b_0 + b_1 d_0^2 + b_2 d_0^2 l + b_3 d_0 l^2$
Spurr (Spurr, 1952)	$V = b_0 + b_1 d_0^2 l$
Ogaya (Dieguez Aranda et al., 2003)	$V = b_1 d_0^2 + b_2 d_0^2 l$
Hoenald-Krenn (Hohenald, 1936)	$V = b_0 + b_1 d_0 + b_1 d_0^2$

V: volume of the branch (cm^3); d_o: base diameter of a branch (cm); l: length of a branch (cm)

To determine the volume function that provides the best fit, the coefficient of determination (R^2), standard deviation (sd) and mean absolute error (MAE) were calculated. The material used in this trial was a digital caliper and a tape measure with precision 0.01 mm and 0.001 m, respectively.

4.1.2. Crown volume estimation, biomass prediction models

Without destructive sampling, the real volume of a tree crown could not be measured. The apparent volume was determined using basic parameters: crown diameter, total tree height and distance from soil to the crown collected during field study. Next, equations for 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 5) (Dieguez Aranda et al., 2003).

Table 5. Growth models of tree crowns

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)

Apparent volume of a tree crown calculated from measurements taken manually at field, was related with data obtained by the TLS and biomass yielded from pruning operations. These tests were performed, in order to verify the accuracy of both methodologies and possible relationship of apparent crown volume with quantity of yielded biomass.

4.1.3. **Statistical analysis**

Following statistical analysis were performed on data obtained in field tests:

Analysis of variance (ANOVA) has been performed to observe if there is a significant difference between the means of analyzed groups. The confidence level used in the tests was 95.0%. Homoscedasticity was verified by analyzing the residual plots generated by the Statgraphics software (Villafranca and Ramajo, 1993). The normal distribution of analyzed groups was also tested by the Statgraphics software by verifying if the skewness and kurtosis values are within -2, +2. In addition, the Shapiro-Wilks test has been performed by means of XLStat software. The ANOVA test allowed studying the influence of several factors on the obtained parameters. For example, in some cases, trees of same species were studied in different location conditions. It was verified, if the location has influence on the residual biomass and dendrometric parameters. Also measurement methods were compared by means of this test.

A variety of regression models were developed in order to predict residual biomass from plant measurement. Regression equations used several explicative parameters, such as diameter at breast height, crown diameter, total height or a combination of these variables. In this study, the outliers have been detected by a specific application of the Statgraphics software. The normality of residuals was verified through residual plot analysis. The independence of residuals was checked by analysis of residual plots or the Durbin-Watson test generated by the Statgraphics software. The goodness of fit of the regression models was studied by the coefficient of determination, standard deviation and mean absolute error. The multiple regression models for each species which gave highest R^2 have been validated. For that, two independent data sets have been organized: one set (n=25) to generate the model and one set (n=5) for its validation. These models are marked with an * and some validation results are attached in the annexes. A t-test has been used to compare the mean of real values and values calculated by a regression model and an analysis of residual plots has been performed.

All statistical tests were performed with Statgraphics 5.1 and XLStat software. It is necessary to emphasize, that the accuracy of developed equations is determined in the context of data used in their construction. There is no guarantee, that these prediction models will apply equally well to an independent sample. Developed regression models will best represent urban forests, where the data were originally collected. Using developed equations in other geographic areas, runs risk of unknown error. Errors may also appear, if the prediction equations are used to estimate biomass of trees, whose parameters values are outside the sample range, or if the tree shape or form deviates significantly from the sample. Nevertheless, the types of equations and influent factors will be similar in all cases. Only it will be necessary to particularize the coefficients from specific trials.

4.1.4. **Studied vegetal material**

In this research five species of Mediterranean urban areas were studied:

a) *Morus alba*

Morus alba L. known as white mulberry is a species of the family *Moraceae*, genus *Morus*. It is native to India and central Asia. Introduced in the VI century in Europe, it is popular in the south of the continent. Reaching up to 15-18 m in height, up to 1.5 m in diameter of the base of the trunk, it is characterized with a broad crown with highly branched long main branches (De La Torre, 2001, www.floraiberica.org). It is a deciduous tree, with big, cordate at the base and rounded to acuminate at the tip leaves. The bark is gray, turning cracked over the years (López Lillo et al., 2006). The flowers are single-sex catkins, with catkins of both sexes being present on each tree. It is characterized with slow growth, resistance to extreme temperatures as well as a strong, resistant to humidity changes and well burning wood. *Morus alba* is cultivated in orchards and as ornamental tree in streets, city parks and towns (López González, 2007).

All sampled trees of *Morus alba* were pruned each year under uniform type of pruning practices. Individuals located on the street, were pruned under topping type of practice, while those located in city parks under annual maintenance type of pruning.

- Topping type of pruning consists of removing a major part of the canopy from the tree and leaving mostly branch stubs (Michau, 1987). Topping is a practice that causes harm to trees and should be avoided. This practice often appears in the urban forests as a consequence of a bad choice of species, lack of space, presence of utility lines, lack of light and risk of accidents do to falling branches (Gil-Albert, 2001). This practice results in the development of epicormic sprouts and unnecessary injuries (Figures 3 and 5).

- Annual maintenance is a light pruning that allows preserving the desired volume and shape of the tree by eliminating the annual sprouting. These operations, if carried out annually in the same spot, after several years, lead to the formation of thickenings at the end of the branch. These thickenings may become necessary to be removed after a few years. Properly done every year, this type of pruning does not provoke problems. In order to avoid the formation of the thickenings, the cut must be done every year some centimetres further on the branch (Michau, 1987) (Figures 4 and 6).

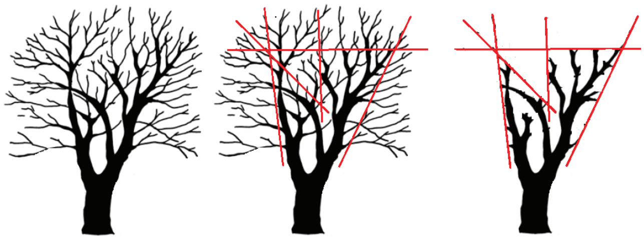


Figure 3. Topping applied to *Morus alba* trees, Bedker et al., 1995 adapted (sheme)

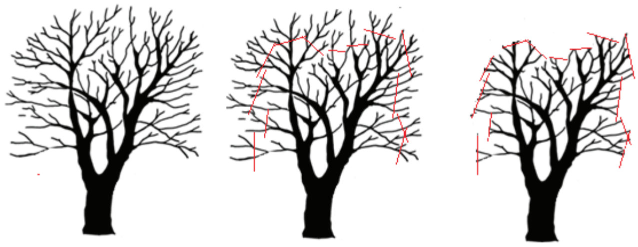


Figure 4. Annual maintenance applied to *Morus alba* trees, Bedker et al., 1995 adapted (sheme)

Figure 5. From left to right: Topping of *Morus alba*: before; after

Figure 6. From left to right: Annual maintenance of *Morus alba*: before; after

b) *Platanus hispanica*

Platanus hispanica Münchh. (*Platanus acerifolia, Platanus hybrida*) is a tree in the family *Platanaceae*, genus *Platanus*. It is thought to be a hybrid of *Platanus orientalis* native to south east of Europe and south west of Asia: Macedonia, Cyprus, north Persia, Afghanistan and the Himalayas, and the *Platanus occidentalis* native to the Atlantic zone of the United States (De La Torre, 2001, www.floraiberica.org). Other authors argue that it may be a cultivar of *Platanus orientalis* (López González, 2007). *Platanus hispanica* is a large deciduous tree that can exceed 30 m in height. The bark is usually pale green, yellow and grey, smooth and exfoliating with characteristic irregular forms. The tree crown is oval in young trees and turns round with age. The leaves are broad, palmately lobed. The flowers are borne in dense spherical inflorescence on a pendulous stem, with male and female flowers on separate stems. The wood is hard, fibrous, resistant and characterized as a good fuel. This species requires light, fertile and fresh soils. 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). *Platanus hispanica* is an extensively cultivated ornamental, parkland and roadside tree in the temperate regions, widely observed in linear plantations in streets as well as isolated in gardens (Ballester-Olmos y Anguís, 2009). It is characterized by a rapid growth, great ease for transplantation and good resistance to pruning operations (López González, 2007, López Lillo et al., 2006).

All sampled trees were pruned each three years under uniform crown raising type of pruning practice. This type of pruning consists of removal of lower branches in order to provide crown elevation clearance for pedestrian and vehicle traffic as well as open views, visibility of lights and signs (Michau, 1987). The lower lateral branches should be cut down systematically every year, but without eliminating more than those that are clearly in excess until the trunk reaches 1.5-2 m in height (Gil-

Albert, 2001). Crown lifting should be performed on young and medium-aged trees. This prevents the low branches from growing to a large diameter. The wounds heal better than in old trees (Bedker et al., 1995). The regulation of the crown elevation is designed to adapt the tree to the different situations where it is situated, as well as to respond to the aesthetic requirements (Michau, 1987) (Figures 7 and 8).

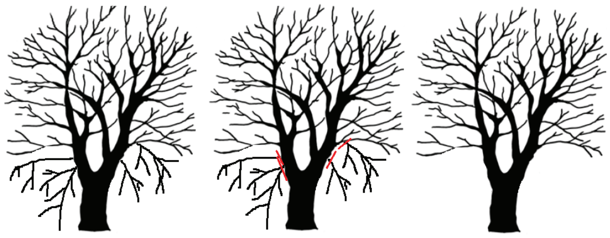


Figure 7. Crown raising applied to *Platanus hispanica* trees, Bedker et al., 1995 adapted (scheme)

Figure 8. From left to right: Crown raising of *Platanus hispanica*; residual transport

c) *Sophora japonica*

Sophora japonica L. also known as *Styphnolobium japonicum* and Pagoda Tree is a species in the family *Fabaceae*, genus *Styphnolobium*. *Sophora japonica* is native to eastern Asia and a popular species in almost all Europe. It is a deciduous, fast growing tree, which reaches up to 25 m in height (www.floraiberica.org). The tree crown is wide and rounded. The bark is dark brown with shallow longitudinal cracks. The leaves are pinnate with 9-13 leaflets. Cultivated as ornamental or shade tree in streets, city parks and towns, often accompanies the *Robinia*, which has a very similar appearance. It is appreciated for flowering in late summer, after most flowering trees have finished and its resistance to cold as well as heat and dryness (López González, 2007). Its beautiful deep green colour foliage is not attacked by insects. The advantage over *Robinia* is to give a denser shade. For this reason, it is widely used in urban zones (De La Torre, 2001).

All sampled trees of *Sophora japonica* were pruned each year under uniform topping type of pruning practice like *Morus alba* . Topping type of pruning consists of removing the major part of the canopy from the tree and leaving mostly branch stubs (Michau, 1987). This practice often appears in the urban forests as a consequence of, lack of space, presence of utility lines, lack of light and risk of accidents do to falling branches (Gil-Albert, 2001). These practices result in the development of epicormic sprouts (Bedker et al., 1995) (Figures 9 and 10).

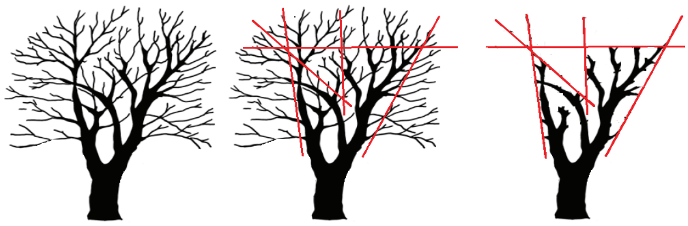


Figure 9. Topping applied to *Sophora japonica* trees, Bedker et al., 1995 adapted (scheme)

Figure 10. From left to right: Topping of *Sophora japonica*: before; after

d) *Phoenix canariensis, Phoenix dactilifera*

Phoenix dactilifera L. (called date palm) and *Phoenix canariensis* hort. ex Chabaud. are species in the palm family *Palmae (Arecaceae)*, genus *Phoenix* (www.floraiberica.org). Palms, posses a number of characteristics, which allow differing them from other plants. The following summary will focus on the characteristics of selected parts of the palm plant.

Trunk

The *Phoenix dactilifera* trunk, also called stem or stipe is vertical, cylindrical and columnar. The girth of the trunk is equal all the way up and does not increase once the canopy of fronds has fully developed. The average circumference is estimated at 1-1.10 m and no ramification is observed. The date palm trunk is brown, lignified and covered for several years with the bases of the old dry fronds that make it rough in touch. With age, these bases obtain smoother appearance with visible cicatrices.

Vertical growth of date palm is provided by its terminal bud, called phyllophor. Data on the height of the trunk differ according to the author and are estimated at 15-20 m and in case of occurrence in their natural environment may reach up to 45 m (Ibañez, 2007; FAO, 2002). However, in case of a nutritional deficiency mainly cause by drought, the terminal bud may experience an abnormal growth resolving in shrinkage of the trunk (FAO, 2002).

Leaves

The date palm has large evergreen leaves that are pinnately or feather-shape compound and spirally arranged at the top of the trunk forming a crown. Their properties differ, depending on variety, age and environmental conditions. An annual formation of new leaves is estimated at the level of 10-26 units and the average life time at 3-7 years. Depending on the distribution within the palms crown, it is estimated that 50% of total leave amount are green and photosynthetically active leaves located on the outside, 40% white juvenile leaves placed on the inside and the rest 10% growing green leaves based in the centre. It is estimated that an adult date palm has 100 to 125 green leaves with the length 3-6 m (FAO, 2002).

The pinnate leaf of the date palm is composed of the following parts:

- the sheathing base or leaf base (this part embraces more or less the trunk, or is attached to it). The sheath consists of white connective tissue ramified by vascular bundles which during the growth of the frond largely disappear. In result, are left dried, brown vascular bundles, a band of tough, rough fibre attached to the lateral edges of the lower part of the midribs of the leaves,
- the leaf stalk or petiole (connecting part between the sheathing base and blade often with no sharp distinction between them),
- blade, rachis or midrib (continuation of the leaf stalk, divided into leaflets which are arranged along both sides in the manner of a feather),
- leaflets (between 120 to 240 per leaf, entirely lanceolate and folded longitudinally. The length of the leaflets varies from 15 to 100 cm and width from 1 to 6.3 cm. Spines may reach up to 20 or 24 cm in length (Del Canizo, 2002; Blombery et al., 1989, FAO, 2002).

In case of palms, sick, old or dead leaves do not drop on their own, but need to be removed under pruning.

Phoenix canariensis also known as the Canary Island date palm is native to Canary Islands. Its stipe reaches 20 m in height and 30-40 cm in diameter. The pinnate leaves have 5-6 m in length (López Lillo et al., 2006). It is widely planted as an ornamental tree in the temperate regions of the world. In comparison with the date palm, the *Phoenix canariensis* has a thicker and shorter stipe, greener and broader leaves (De La Torre, 2001, Ballester-Olmos y Anguís, 1996), as well as much smaller fruit reaching1-2.3 (2.5) cm in length (López González, 2007). *Phoenix canariensis* adapts to different types of soils (Ramoneda et al., 1997). It is resistant to hot and dry environments. Adapts well to drought, for this can be grown in template, subtropical and tropical regions (Jones, 1999).

Both *Phoenix canariensis* and *Phoenix dactilifera* were pruned annually. Annual pruning of palm trees consists of reducing the canopy by removing dead, damaged or unwanted fronds and inflorescences. Sometimes, it is necessary to adapt the dimensions of the palms canopy to the available space. In these cases, fronds that cause problems are removed selectively. It is always important to remove the lowest amount of fronds (Figures 11 and 12).

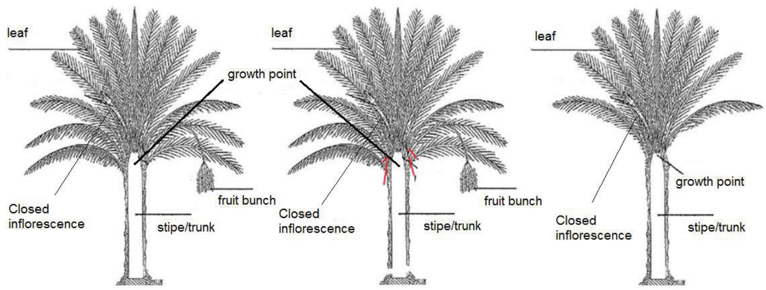


Figure 11. Annual pruning of palm trees, FAO, 2002 adapted (scheme)

Figure 12. From left to right and up to down: Annual pruning of *Phoenix canariensis* before; after*; Phoenix dactilifera* pruning; residuals

Because of large areas where these species are cultivated in Mediterranean urban forests, the quantification and assessment of their residuals becomes important.

4.2. LIDAR APPLICATION

The instrument used in field trials was a Leica ScanStation 2 laser scanner, based on time of flight technology with a dual-axis compensator, high scanning speed (50,000 points per second) and a high resolution camera (www. leica-geosystems.com). Its main technical characteristics are described in Table 6. The equipment consists of the following accessories: laptop, tripod, batteries, aiming marks, etc. (Figure 13).

Table 6. Main characteristics of the equipment Leica ScanStation 2 laser scanner (www. leica-geosystems.com)

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 0-50 m < 1 mm max. Fully selectable horizontal and vertical
Field of view (horizontal / vertical)	360º / 270º	

Figure 13. From left to right: Leica ScanStation 2 equipment with necessary accessories; tripod-mounted HDS target; scanned target

4.2.1. Field data collection and processing

In this work 30 sample trees of *Platanus hispanica* were selected in Alcudia, (39º28`50``N, 0º21`59``W), a city located in the province of Valencia (Spain) in the main Av. del Comte Serrallo. This species was selected due to its widespread deployment in urban areas of temperate regions (López González, 2007) and significant volumes of residual proceeding from pruning. The sampled trees were placed on both sides of a road (Figure 14). The width between the tree lines was 12m. The mean distance between trees of the same line was 20 m. This allowed the differentiation between the point clouds of the different trees, which was important for scanning and further processing tasks. Prior to data acquisition a pre-selection of sample trees was made to assure that all individuals would be pruned under uniform crown raising type of pruning practice after the scanning process had finished. Most of the trees were scanned from at least two viewpoints, following a zigzag route to register all sides of each sample tree. Nevertheless, some of them were only scanned from one viewpoint due to trees dimensions, proximity to buildings, etc.

The average age of the studied trees was between 10-12 years. The height was between 8.94 m and 12.8 m, and crown diameter between 4.27 m and 12.12 m. These sizes made it difficult to measure the crown tops of the sample trees with the TLS due to their proximity. Despite these constraints, it is considered that the geometry of the shots was suitable.

Figure 14. Tree distribution

Thirteen stations were used to measure the 30 sample trees. The device was levelled at each station, and after starting the computer, several photographs of the area were taken to define the scanning windows. Then, basic settings of the TLS scanning, such as ambient temperature, atmospheric pressure, and scan resolution (points every 5mm) were selected. In each station, objects or surfaces around the trees were also scanned, such us street, walls, parked or moving vehicles, people (Figure 15).

Figure 15. From left to right: picture of scanned trees in the urban area; obtained scan data, where elements different to the tree must be filtered

Each tree was measured using at least two stations. To merge the different point clouds taken from the different stations, a minimum of 4 point targets or reference marks were measured. These points were used as link points. Next an automatic Registration command was used in Cyclone v.6 software to compute the optimal alignment of the targets so that all of them are aligned as closely as possible. The absolute mean errors of the fitting operations were between 0.003 m and 0.018 m. The error of fitting operations shows how precisely the ScanWorlds and targets are adjusted. After merging data, each tree was recorded in a single file to facilitate processing operations. Scanning data were processed with Cyclone v.6, Leica specific software.

First, the filtrate and removal of unwanted items was made. These are defined as points not belonging to the trees (vehicles, buildings, people, birds, traffic signs, etc.) and which were manually removed with Cyclone v.6 software tool (polygonal fence model-delete inside). Because the fieldworks were conducted over several days and meanwhile precipitation occurred, permanent reference marks in the study area could not been left. Two records were defined, the first among the first 5 stations and the second between the remaining 8. A single point cloud was formed from them.

As an initial idea to carry out the characterization of each tree, it was thought to use various 3D software available on the market. In this way, it was intended that the acquisition of various geometric features could be performed interactively and quick. These tests were carried out using 3DReshaper, Rapidform and Leica-specific Cyclone. Since conventional 3D programs have limited tools, mainly to obtain volumes, some final results were obtained with MATLAB.

4.2.2. **Extraction of tree parameters from TLS point clouds**

The primary tree structure parameters that were extracted from the TLS point cloud were the total tree height, crown height, trunk height and crown diameter. Due to the fact that the TLS permitted to acquire data from different viewpoints, it was feasible to determine tree dimensions from different perspectives. Three files for each tree were made: whole tree (A [No]. xyz), tree trunk (A [No.] T.xyz) and tree crown (A [No.] C.xyz) (Figure. 16). The operator selected manually from the 3D point cloud which points belong to the crown and which points belong to the stem.

Figure 16. From left to right: whole tree (A [No]. xyz); tree trunk (A [No.] T.xyz); tree crown (A [No.] C.xyz)

a) Total tree height

The total tree height was calculated using the A [No.].xyz file. It was estimated using the difference in laser pulse reflection from the top of the crown (corresponding to "peak" of the crown) and the ground (corresponding to the base of the trunk). The result was registered in m.

b) Trunk height

The trunk height was calculated using the A [No.] T.xyz file. It was estimated using the difference in laser pulse reflection from the top of the trunk and the ground (corresponding to the base of the trunk). The result was registered in m.

c) Crown height

When calculating the height of the crown, the difference between total tree height and trunk height parameters was estimated. The result was registered in m.

d) Crown diameter

In order to obtain crown diameter, the average of the longest and the perpendicular diameters was calculated. To analyze the crown diameter, the point cloud was displayed as a projection on the XY plane. A reference point in the form of the center of the trunk was found. This was obtained using trunk specific point cloud (A [No.] T.xyz). All points located within 5cm from the top of the trunk were selected to avoid risk of insufficient point number for the study (Figure 17). The average of X and Y coordinates was calculated, what yielded a reference point for diameter calculation. The reference point is considered accurate, since there is no way of knowing the true central point without destructive sampling. The following figure shows an example of information contained in files that were used for these calculations and the selected area.

Figure 17. A4T.xyz file loaded in Cyclone for trunk centre calculation

For diameter selection, the A [No.] C.xyz point cloud was projected onto the XY plane (Figure 18). Following formulas were applied (Equation 2, 3, 4 and 5):

Increment of X, Y:

$$\Delta x = X_m - X_{pc} \qquad (2)$$

$$\Delta y = Y_m - Y_{pc} \qquad (3)$$

Where:
X_m, Y_m = coordinates of the centre of the trunk
X_{pc}, Y_{pc}= coordinates of each point

Distance from center of the trunk to selected scanned point in the plant:

$$\rho = \sqrt{\Delta x^2 + \Delta y^2} \qquad (4)$$

Angle from the center point to the selected point:

$$\alpha = \mathrm{arctg}\frac{\Delta x}{\Delta y} \cdot \left(\frac{180}{\pi}\right) \qquad (5)$$

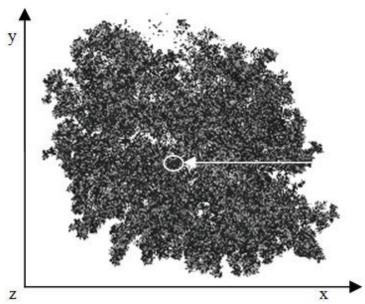


Figure 18. [No.] C.xyz point cloud projected onto the XY plane

This yielded the polar coordinates, assigning to each point a distance and an angle. In the following operations, the value of the angles was changed so that it was between 0º and 360º. Next the tree crown positioned at the centre of the trunk was divided into sections with the same centre point and an angle of 5 degrees. This provided a total of 72 sections. The section with the most exterior point was selected (Figure 19). Knowing the angles between each section, all radiuses were calculated. In the event that no radius could be found within the search angle, a new radius was recalculated from the two closest stored radiuses. The diameters were obtained by adding the opposite half of each radius. In this way for the first diameter the radius set between 0° and 5°, and its opposite, between the $180^{th\ o}$ and $185^{th\ o}$ were found and summed. In the same way the rest of the diameters were determined, until a total of 36 diameters were obtained.

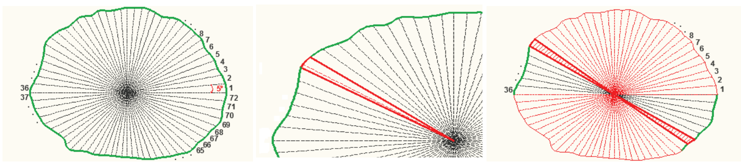


Figure 19. Phases of diameter calculation

The arithmetic mean of the longest (corresponding to section with most exterior point) and perpendicular diameters was considered the crown's diameter for further calculations. It is important to keep in mind, that when applying this methodology in the field, the largest and the perpendicular diameters that are selected may not be accurate. Results obtained with programming will always be more accurate than those obtained manually at field. Furthermore, it should be noted that when measuring crown diameter, the line should pass through the centre point of the trunk. The result was registered in m.

The tree dimensions extracted from TLS point clouds were compared with *in situ* classical dendrometrical measurements applied on the same individuals. This allowed comparing both methodologies by a variety of regression models. To determine models that provided the best fit, the coefficient of determination (R^2), standard deviation (sd) and mean absolute error (MAE) were calculated.

4.2.3. Methods for determination of crown volume

Different approaches to calculate the crown volume were performed. To do this, four processing algorithms were implemented using MATLAB (MathWorks, Inc.). The accuracy and the processing time of each one of them was analyzed (Figure. 20):

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

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

- *Volume calculation by sections* (Method 3): Division of the crown's point cloud into sections of 10cm 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 10cm.

- *Rasterization in voxels* (Method 4): Transformation of the point cloud into small units of volume using a grid in three-dimensional space (voxel).

In Figure 20, the geometrical shapes for crown volume calculation are depicted for each method.

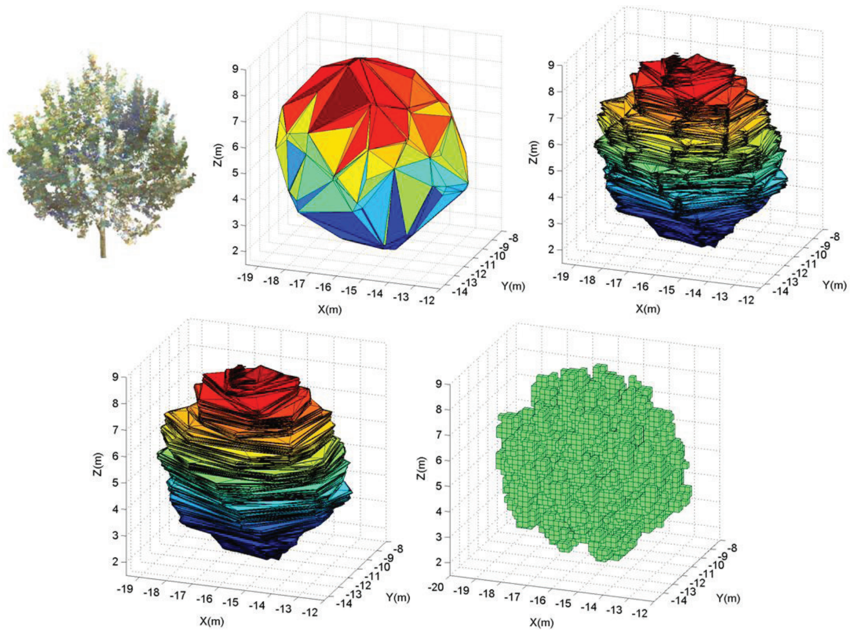


Figure 20. Representation of the four algorithms used to derive crown volume from TLS data. From left to right and top to down: Picture of the scanned crown; global CH; CH layers; triangulation by sections; voxels

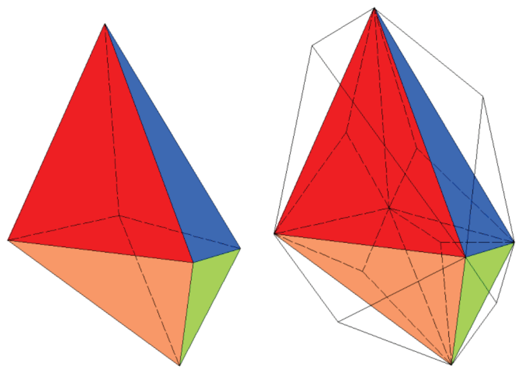
Method 1 *(Global convex hull)*

The convex hull of a set of points in a plane or in a space is the smallest of the areas or volumes that contain the examined points (Graham, 1972). For three-dimensional space, convex hull is the boundary of a closed convex surface generated by 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, Conquer and QuickHull. Of these, was used convhulln function based on the QuickHull algorithm implemented in MATLAB. This algorithm removes the points that are not located in the boundary of the closed convex hull, such as interior points. To do this, the following steps were carried out:

Step 1: Six exterior points of the cloud are selected (maximum and minimum X, Y, Z) generating an irregular octahedron. All points within this polyhedron do not belong to the boundary. The points outside this octahedron are divided in eight separated regions considering each side (Figure 21a).

Step 2: The point with the largest distance to the plane formed by an octahedron side is selected in each region. In this way, 8 new points are selected to generate a new figure of 14 vertexes (6 initial points from step 1 and other 8 from step 2). New 24 triangles are formed between the vertexes (Figure 21b). The points within the new figure are also removed.

Step 3: The previous steps are repeated selecting new points whose distance to the new triangle sides are maximum and generating 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, whose volume can be calculated.



(a) **(b)**

Figure 21. a,b. Initial steps for convex hull formation

The main inconvenience 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 layers*)

This method is based on the same algorithm as Method 1 applied to layers of 5 cm in height.

From the minimum height of the crown, all points located between 0 and 5 cm in height are selected and the convex hull method is applied (Method 1). Then, this method is applied considering the points located between 5 and 10 cm. The process is repeated for every following layer of 5 cm in height. The final volume is obtained adding the single volumes of all layers. The operation number is higher than in Method 1 given that the convex hull function is applied to each layer.

Method 3 (*Volume calculation by sections*)

The tree crown is divided into sections of 10 cm in height. For each section, the section area is calculated. The volume of each section is obtained using the equation 6, where *S1* and *S2* are the areas of the consecutive sections and h_s is the separation between sections (10 cm):

$$V = \frac{S1 + S2}{2} \cdot h_s \qquad (6)$$

Firstly, from the lowest point of the crown's point cloud, all points within 10 cm height are selected. These points form the first section. Within this section, two new sections are formed by points located within 2 cm from top of the section and 2 cm from bottom of the section. Then, a triangulation is applied to the points considered in the same horizontal plane and the area of the section is calculated. This step is repeated for every 10 cm of height of the crown.

Method 4 (*Rasterization in voxels)*

Voxel (*volumetric pixel*), is a minimum discrete volume that can be processed in a tridimensional object (Hosoi et al., 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. The volume of each voxel is added to calculate total volume and the shape of the crown is obtained. To calculate the crown volume considering the voxel concept, the following steps were performed:

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

Step 2. The coodinates X_{min} and X_{max} of first voxel are labelled. Then, all points with coordinates X between those *X-limits* create a set associated to the first sections (S_1) in the YZ plane.

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

Step 4. The coordinates Z_{min}, Z_{max} of the first voxel are also calculated and from points selected in step 3, only those whose *Z* coordinates between those limit values are included in the first voxel *V1*. The coordinates of the voxel *V1* and the presence-absence of points within it are stored in a matrix. The same steps are followed for the rest of voxels *(V2 to Vn)* of the *C1 – S1*. After, this algorithm is applied from the column *C2* to *Cn*. Then this algorithm is applied from *S2* to *Sn*.

The final result is a matrix of coordinates for each voxel indicating presence-absence of points inside. The total volume is obtained multiplying the number of voxels with points inside by the volume of a voxel (80 000 cm^3). The structure of the tree crown can be depicted from the location of each voxel.

The four methods allow the calculation of crown volume and other dendrometric variables such as tree height, trunk and crown height and crown diameter. These variables allow establishing relations with classical manual measurements as well as residual biomass from pruning.

4.2.4. **Volume calculation by classic dendrometry**

The apparent volume of a tree crown can be estimated in terms of its adjustment to 3 geometric shapes of known mathematical formulas, such as a cone, a paraboloid and a hemisphere explained in Table 7. These three forms are used mainly in traditional forests and may misrepresent urban trees, since the development conditions are not the same in natural areas and cities.

Volumes of 30 individuals of *Platanus hispanica* obtained by classical dendrometry and three-dimensional models generated from data recorded by a TLS were compared.

The cone equation and paraboloid equation are proportional, being 2/3 the proportionality factor. Between paraboloid equation and hemisphere there is a relationship (Equation 7), which is dependent on the diameter and crown height. Therefore, this factor is not constant but will show a population variation that is studied in this thesis defining its mean and standard deviation for *Platanus hispanica* trees.

$$K = \frac{2}{3} \cdot \frac{dc}{hc} \qquad (7)$$

Where
K = proportional factor between the paraboloid volume and hemisphere
dc = crown diameter (m)
hc = distance from soil to the crown (m)

On each point cloud, four different algorithms to calculate volumes of tree crowns were applied. These were compared with three geometrical shapes. The method that provided best apparent volume in less processing time and increased automation facing management-related applications was defined.

4.3. WOOD CHARACTERIZATION

4.3.1. Fuel specification

The specification of biomass was based on the norm UNE-EN 14961-1. According to Table 1 of this norm, the classification of the origin and sources of solid biofuel examined in this thesis are the following:

"1. Woody biomass
1.1.Woody biomass from forest, plantation and other virgin wood
1.1.7.Wood from gardens, parks, maintenance of roadsides, vineyards and orchards"

According to the specification of solid biofuels based on shape and properties, the analyzed material is classified as followed (Table 7).

Table 7. Specification of properties of wood logs

Origin: According to paragraph 6.1 and Table 1 of UNE-EN 14961-1.	Woody biomass: *Morus alba* *Phoenix canariensis* *Phoenix dactilifera* *Platanus hispanica* *Sophora japonica*	
Commercial form	Logs, wood	
Dimensions		
Length (L) (maximum length of a single cut), cm	*Morus alba* *Phoenix canariensis* *Phoenix dactilifera* *Platanus hispanica* *Sophora japonica*	L 100+, (max. 380 cm) L 100+, (max. 462 cm) L 100+, (max. 496 cm) L 100, 100 cm ±5 cm L 100+, (max. 180 cm)
Diameter (D) (maximum diameter of a single cut), cm	*Morus alba* *Phoenix canariensis* *Phoenix dactilifera* *Platanus hispanica* *Sophora japonica*	D10, 2 cm ≤D ≤10 cm D10, 2 cm ≤D ≤10 cm D2-, D<2 cm
Humidity (M) (according to received mass)	*Morus alba* *Phoenix canariensis* *Phoenix dactilifera* *Platanus hispanica* *Sophora japonica*	M45 M55+ (Max. 74.82%) M55+ (Max. 71.03%) M45 M45
Volume or weight, m^3 stacked or loose or kg as received	*Morus alba* *Phoenix canariensis* *Phoenix dactilifera* *Platanus hispanica* *Sophora japonica*	Mean dry weight 31.13 kg/street tree; 77.78kg/ park tree Mean dry weight 24.67 kg/tree Mean dry weight 36.13 kg/tree Mean dry weight 23.98 kg/tree Mean dry weight 18.07 kg/tree
Proportion by volume of stumps	*Morus alba* *Phoenix canariensis* *Phoenix dactilifera* *Platanus hispanica* *Sophora japonica*	Whole (unsplit) Whole (unsplit) Whole (unsplit) Whole (unsplit) Whole (unsplit)
Cut surface	*Morus alba* *Phoenix canariensis* *Phoenix dactilifera* *Platanus hispanica* *Sophora japonica*	Smooth and regular Smooth and regular Smooth and regular Smooth and regular Smooth and regular
Wet and rot	*Morus alba* *Phoenix canariensis* *Phoenix dactilifera* *Platanus hispanica* *Sophora japonica*	No No No No No

4.3.2. ***Determination of moisture content***

Moisture occurs in wood in form of free water in cell cavities and absorbed water in cell walls (Husch et al., 2003). The evaluation of drying process was done according to the norm UNE-EN 14774-2. The process took place in two types of conditions. Open-air drying was carried out in laboratory environment with average temperature 21.32ºC and relative humidity 42.41%. A daily record of results took place until the stabilization of weight was obtained. When oven drying, samples were placed on metal trays and located in a stove with controlled temperature (105+-2) ^{o}C. The drying time didn't exceed 24h in order to avoid possible unnecessary loss of volatile substances. For sample preparation and result registration an electronic balance was used with the precision of 0.01 g. A number of 30 samples per species were examined.

Total moisture content in wet basis was calculated with the following equation (8) (UNE-EN 14774-2). The results were reported as percentage.

$$M_{ar} = \frac{(m2 - m3) + m4}{(m2 - m1) + m4} \cdot 100\% \qquad (8)$$

Where
M_{ar}= moisture content of biofuel (%)
m_1= mass of empty drying container (g)
m_2= mass of drying container and sample before drying (g)
m_3= mass of drying container and sample after drying (g)
m_4= mass of packaging moisture (g)

4.3.3. **Sample preparation**

To carry out the laboratory analysis the samples were prepared as follow. The analyzed *Morus alba, Platanus hispanica, Sophora japonica* branches were divided into 4 diameter classes and the *Phoenix canariensis* and *Phoenix dactilifera* branches into 3 diameter classes. The diameter classes represent the base of the branch section, midway sections and the upper end section. Next, various wood samples within a diameter section were chipped with a hammermill and stored for laboratory characterization. Within each species and diameter class, convection dried and open air dried samples were tested for calorific value and CHNS composition.

4.3.4. **Determination of calorific value**

Samples from urban species were analyzed by means of an adiabatic calorimeter. This test was based on the norm UNE-EN 14918. A minimum number of 16 samples per *Morus alba*, *Platanus hispanica*, *Sophora japonica* and a minimum number of 12 samples per *Phoenix canariensis* and *Phoenix dactilifera* were examined. The theory of operation of the instrument is explained below.

To measure the calorific value of various organic materials collected during field trials a LECO AC500 Automatic Calorimeter was used. The calorific value of each sample was determined by its combustion in a controlled environment at 3000 kPa. The heat released in the process was proportional to the calorific value of the examined substance.

The procedure of trial consisted of the following stages:

1. Sample with weight between 100-1000 mg is prepared.
2. Sample is placed in a combustion vessel. The combustion vessel is located in a water bucket surrounded by a jacket and the sample is ignited. During the analysis the water temperature is measured by an electronic thermometer with a resolution of 1/10.000 of a degree. Some energy exchange may occur between the outside environment and water surrounding the combustion vessel. For this, a continuous monitoring of the buckets and jackets temperatures is held and a correlation to the result is applied.
3. The water temperature is measured by a microprocessor every 6 seconds. An analogue to a digital convertor converts the output into a number stored in the memory.
4. The difference in water temperature between pre-fire and post-fire is processed by a computer. Results are presented as cal/g (LECO, 2009a).
5. Trial is repeated for all samples.

4.3.5. **Determination of total content of carbon, hydrogen and nitrogen**

Samples of examined species were analyzed by means of CHN determinators. This test was based on the norm UNE-EN 15104. A minimum number of 16 samples per *Morus alba*, *Platanus hispanica*, *Sophora japonica* and a minimum number of 12 samples per *Phoenix canariensis* and *Phoenix dactilifera* were examined for each of the elements. The theory of operation of the instrument is explained below:

1. Sample with weight between 100-1000 mg is prepared.
2. The analyze cycle is divided into three phases: purge, combust and analyze.
3. Purge phase: the encapsulated sample is placed in the loading head, sealed and purged of atmospheric gases that entered during sample loading. The ballast volume and gas lines are also purged.
4. Combust phase: sample is dropped into the furnace with temperature 950^{o}C and next flushed with oxygen for rapid and complete combustion. The combustion products pass through an afterburner (850^{o}C) for further oxidation and particulate removal. Next combustion gasses are collected in the ballast (collection vessel).
5. Analyze phase: sample is combusted in the furnace with oxygen flow. Combustion gases are collected in the ballast. Next the homogenous combustion gases in the ballast are purged through the CO_2 and H_2O infrared detectors and the 3cc aliquot loop. After gas equilibration C is measured by the CO_2 detector and H is determined as water vapour in the H_2O detector. The gases in the aliquot loop are transported to the helium carrier flow, swept through hot copper for O removal and NO_X to N_2 change. Next they flow through Lecosorb and Anydrone in

order to remove CO_2 and H_2O. Nitrogen content is determined in a thermal conductivity cell. The results are reported as percentage/ppm or gram (LECO, 2009b).

6. Trial is repeated for all samples.

4.3.6. **Determination of total content of sulphur**

The sulphur content in the examined samples was determined with a Tru-Spec Add-On Module. A minimum number of 16 samples per *Morus alba*, *Platanus hispanica*, *Sophora japonica* and a minimum number of 12 samples per *Phoenix canariensis* and *Phoenix dactilifera* were examined. This was made in the following steps:

1. Sample with weight between 500-1000 mg is prepared and placed in a combustion boat.
2. Sample is combusted in a combustion system with pure oxygen environment and temperature 1350^{o}C.
3. Sample contained in the combustion boat goes through an oxidative reduction process. This results in the release of sulphur from sulphur-bearing compounds. Sulphur oxidizes to SO_2 and is released into the carrier flow as sample gases.
4. Gases from the combustion system flow through an Anhydrone tube in order to remove moisture, through a flow controller and an infrared detection cell.
5. The cell measures the concentration of SO_2 gas present. The instrument automatically converts the value through an equation stored in the software, taking into account sample weight, calibration and known moisture value. The results are reported as percentage/ppm or gram (LECO, 2009c).
6. Trial is repeated for all samples.

All instruments used in the trials were connected to an external PC and use a Windows-based software program in order to control the operations and data management.

4.3.7. **Determination of wood density**

Wood density is expressed as dry mass of wood substance per unit of green volume. The methodology employed involved the determination of dry weight of samples by convection drying with temperature (105±2)^{o}C until the stabilization of weight after 24 hours. The samples were immerged in a beaker with water. The obtained difference equivalent to the volume of displaced water, equals the volume of the sample submerged (Equation 9) (Husch et al., 2003). The mean and standard deviation were calculated for the obtained densities. The material used for this test was a 250ml beaker, distilled water, electronic balance with precision 0.01 g, a holder for the immersion of wood samples and a number of 5 samples for species.

$$D = \frac{Wd}{Vg} \qquad (9)$$

Where
D= wood density (g/cm^3)
Wd= oven-dried weight of wood (g)
Vg= green volume (cm^3)

4.3.8. **Determination of percentage of bark**

To perform this study several branches of *Morus alba, Platanus hispanica, Sophora japonica* were divided into 4 diameter classes. The diameter classes represent the base of the branch section, midway sections and the upper end section. To determine the percentage of bark, the diameter over bark and the diameter under bark were determined for all analyzed samples within a diameter class (Equation 10). The average percentage of bark was determined within each diameter class. The materials used in this trial were pruning shears, a digital caliper with precision 0.01 mm and a number of 25 samples per species.

$$ba = \frac{dob^2 - dub^2}{dob^2} \cdot 100\% \qquad (10)$$

Where
ba = bark (%)
dob= diameter over bark (mm)
dub= diameter under bark (mm)

5. RESULTS AND DISCUSSION

5.1. ALLOMETRIC PREDICTION OF THE AMOUNT OF RESIDUAL BIOMASS FROM PRUNING

The mean and standard deviation (sd) of quantity of dry biomass obtained per species is shown in the Table 8. It can be noted that there is a high standard deviation for all species. For this, it is verified if better prediction than from the mean can be obtained by indirect methods.

Table 8. Mean values and standard deviation of dry biomass

Species	Mean dry biomass (kg/tree)	sd
Morus alba (street)	31.67	16.88
Morus alba (park)	77.78	29.51
Phoenix canariensis	24.67	7.82
Phoenix dactilifera	36.13	11.37
Platanus hispanica	23.98	15.16
Sophora japonica	18.07	4.25

sd: standard deviation

5.1.1. *Morus alba*

As it was pointed out, the studied *Morus alba* trees were located in two different conditions: street and park. The variable analysis results are presented in Tables 9 and 10.

Table 9. Variable analysis of *Morus alba* trees, street location

Variable	Average	Standard deviation	Standard skewness	Standard kurtosis	Shapiro-Wilks test (P-value)	Maximum	Minimum
Diameter at breast height (cm)	30.12	5.08	0.58	-0.29	0.541	40.70	19.65
Crown diameter (m)	5.45	1.10	0.95	-0.30	0.459	8.10	3.60
Total tree height (m)	8.85	1.49	-1.10	-0.56	0.165	11.10	5.90

Table 10. Variable analysis of *Morus alba* trees, park location

Variable	Average	Standard deviation	Standard skewness	Standard kurtosis	Shapiro-Wilks test (P-value)	Maximum	Minimum
Diameter at breast height (cm)	42.29	12.94	0.92	0.78	0.243	78.90	19.20
Crown diameter (m)	8.62	1.85	1.99	-0.08	0.053	12.50	5.67
Total tree height (m)	9.51	0.78	0.35	-0.71	0.719	11.20	8.10

The variable analysis indicates in this case, that the standardized skewness and kurtosis values are within the range expected for data from a normal distribution. Moreover, all p-values of the Shapiro-Wilks test are bigger than 0.05, what verifies the normality of the data.

Possible dendrometric differences between the two populations were examined by ANOVAs analysis according to diameter at breast height, crown diameter and tree total height (Figure 22).

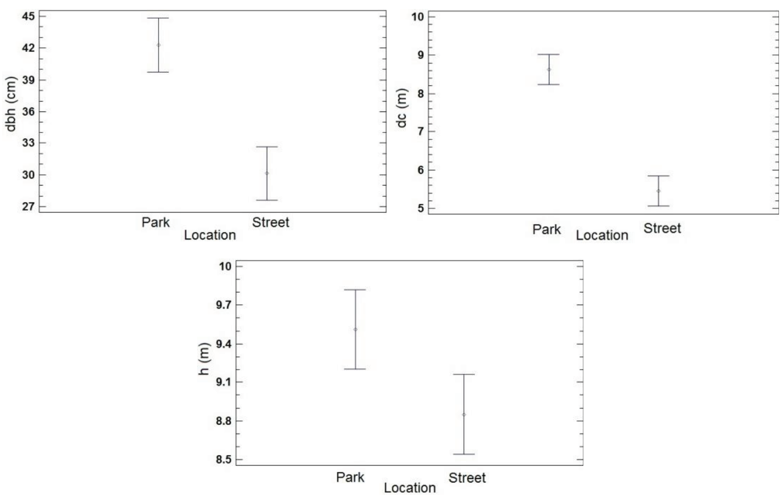


Figure 22. LSD intervals for "Location" factor in *Morus alba* trees at 95% confidence level: dbh: diameter at breast height (cm); dc: crown diameter (m); h: total tree height (m)

According to Figure 22, the two populations of *Morus alba* located in streets and parks were statistically significant different according to all examined dendrometric parameters at the 95.0% confidence level. The park location sample was bigger according to all examined variables. This could influence the biomass analysis.

In this work could be noted that wood formed 100% of total weight of all pruned material before drying, given that the pruning operations were done after the leaves have fallen off. Wood moisture content in wet basis was 46.56% for individuals in park location and 41.42% for individuals in street location. The mean and standard deviation of parameters are presented in Table 11.

Table 11. Mean and standard deviation of dendrometric variables of *Morus alba*

Location, type of pruning	Diameter at breast height (cm)		Crown diameter (m)		Distance from soil to the crown (m)		Total tree height (m)		Dry biomass - wood (kg)	
	mean	sd	mean	sd	mean	Sd	mean	sd	mean	sd
Street location	30.12	5.08	5.45	1.10	2.86	0.40	8.85	1.49	31.67	16.88
Park location	42.29	12.94	8.67	1.92	2.34	0.28	9.51	0.78	77.78	29.51

sd: standard deviation

It is observed that within the sample-tree rage, individuals located in parks are bigger according to all analyzed variables and yield higher quantities of biomass. This sample contained older individuals with wider crowns.

a) Branch form factor and volume functions

Table 12 shows the mean and standard deviation values of the branch form factors obtained for different models. The model that produced a form factor closest to 1 was the paraboloid. This model represented the best fit to characterize the actual form.

Table 12. Mean and standard deviation of form factor of sample branches of *Morus alba*

Model volume	Real volume					
	Huber		Newton		Smalian	
	f	sd f	f	sd f	f	sd f
Cylinder	0.43	0.09	0.43	0.08	0.43	0.08
Paraboloid	0.86	0.18	0.86	0.17	0.86	0.17
Cone	1.29	0.27	1.29	0.26	1.29	0.26
Neiloid	1.73	0.36	1.73	0.35	1.73	0.35

f : mean form factor; sdf : standard deviation of form factor

The variation of the form factor from the base diameter and length of the branches was studied by means of regression models. The coefficients of determination (R^2), standard deviation (sd) and mean absolute error (MAE) are presented in Table 13. The P-values greater than 0.05 (Table 14) indicate, that there is not a statistically significant relationship between the variables at the 95.0% or higher confidence level.

Table 13. Regression model to describe the relationship between f and 2 independent variables do, h in branches of *Morus alba*

Equation	R^2	sd	MAE
f paraboloide = 0.661865 + 0.29047 · do -0.00144258 · l	0.157	0.180	0.133

f: form factor; R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error; do: base diameter of a branch (cm); l: length of a branch (cm)

Table 14. Significance of explicative variables for form factor for *Morus alba*

Dependent variable: f paraboloid Independent variables: do, l				
Parameter	Estimation error	Standard error	T statistic	P-Value
Constant	0.661865	0.286492	2.31024	0.0395
do	0.29047	0.194408	1.49412	0.1610
l	-0.00144258	0.00130746	-1.10335	0.2915

f: form factor; do: base diameter of a branch (cm); l: length of a branch (cm)

Table 15 shows the results of adjusting the volume functions for *Morus alba* branches. For each model, were obtained the coefficient of determination, standard deviation and mean absolute error.

Table 15. Branch volume functions for *Morus alba*

Author	Volume function	R^2	sd	MAE
Naslund (modif)*	$V = -591.746 + 507.093 \cdot do^2 - 2.09281 \cdot do^2 \cdot l + 0.0083961 \cdot do \cdot l^2$	0.96	43.63	26.21
Spurr	$V = 33.2341 + 0.308898 \cdot do^2 \cdot l$	0.85	77.89	52.31
Ogaya	$V = -57.6563 + 58.2544 \cdot do^2 + 0.176836 \cdot do^2 \cdot l$	0.87	75.74	50.88
Hoenald-Krenn	$V = -336.144 + 189.778 \cdot do + 82.168 \cdot do^2$	0.85	83.82	58.38

R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error; V: volume of a branch (cm^3); do: base diameter of a branch (cm); l: length of a branch (cm);* best equation validated with independent data

All volume functions presented high coefficients of determination. The ones that presented the best fit were the Spurr and Naslund. Tables 16 and 17 show detailed statistical analysis of the selected volume functions.

Table 16. Significance of explicative variables for Spurr volume function for *Morus alba*

Dependent variable: V
Independent variables: $do^2 \cdot l$

Parameter	Estimate	Standard error	T statistic	P-Value
Constant	33.2341	44.2206	0.751553	0.4657
$do^2 \cdot l$	0.308898	0.0346072	8.92581	0.0000

V: volume of a branch (cm^3); do: base diameter of a branch (cm); l: length of a branch (cm)

Table 17. Significance of explicative variables for Naslund volume function for *Morus alba*

Dependent variable: V
Independent variables: do^2, $do^2 \cdot l$, $do \cdot l^2$

Parameter	Estimate	Standard error	T statistic	P-Value
Constant	-591.746	120.552	-4.90862	0.0027
do^2	507.093	91.3396	5.55173	0.0014
$do^2 \cdot l$	-2.09281	0.459639	-4.55315	0.0039
$do \cdot l^2$	0.0083961	0.00180676	4.64705	0.0035

V: volume of a branch (cm^3); do: base diameter of a branch (cm); l: length of a branch (cm)

In both cases the P-values of all explicative variables were less than 0.05 and there is a statistically significant relationship between the variables at the 95.0% confidence level. Although the Spurr model has a lower coefficient (R^2=0.85), due to lower complexity, it is considered more appropriate for volume calculation.

According to the presented results can be concluded, that the volume functions allow better approximation than the form factor, which has a big variation (sdf).

b) Regression models for biomass prediction

Following regression models were calculated to predict the amount of residual biomass from pruning operations of *Morus alba* from simple measures such as diameter at breast height, crown diameter and total tree height. Tables 18, 19 and 20 show the relationships obtained in street locations where topping technique was applied. Tables 21, 22 and 23 show the results for maintenance pruning, which was carried out in parks.

Table 18. Regression models to describe the relationship between the pruned biomass (B) and only one independent variable for *Morus alba*, street location

Residual biomass versus diameter at breast height (dbh)	
Type of equation	Equation
Linear	$B = -20.1049 + 1.71883 \cdot dbh$
Quadratic	$B = 4.47144 + 0.0291707 \cdot dbh^2$
Residual biomass versus crown diameter (dc)	
Type of equation	Equation
Linear	$B = -46.1278 + 14.2691 \cdot dc$
Quadratic	$B = -6.90073 + 1.24776 \cdot dc^2$
Residual biomass versus total tree height (h)	
Type of equation	Equation
Linear	$B = -19.9197 + 5.82956 \cdot h$
Quadratic	$B = 3.65834 + 0.348094 \cdot h^2$

B: dry biomass (kg)

Table 19. Multiple regression analysis for *Morus alba*, street location

Residual biomass versus diameter at breast height (dbh)			
Type of equation	R^2	sd	MAE
Linear	0.26	14.70	12.24
Quadratic	0.29	14.43	11.96
Residual biomass versus crown diameter (dc)			
Type of equation	R^2	sd	MAE
Linear	0.87	6.06	4.73
Quadratic	0.87	6.12	4.67
Residual biomass versus total tree height (h)			
Type of equation	R^2	sd	MAE
Linear	0.26	14.72	11.64
Quadratic	0.27	14.62	11.52

R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error

The results (Table 19) indicate a high dependence between residual biomass and crown diameter with a coefficient of determination at the level R^2=0.87 in the linear model. Nevertheless, the biomass doesn’t show dependence with total height nor with diameter at breast height indicating lack of dependence with tree age.

Table 20. Significance of explicative variables for biomass prediction for *Morus alba*, street location

			Estimate	Standard error	T statistic	P-Value
B versus dbh	Linear model	Constant	-20.1049	16.3798	-1.22742	0.2299
		dbh	1.71883	0.536407	3.20433	0.0034
	Quadratic model	Constant	4.47144	8.37095	0.534162	0.5974
		dbh^2	0.0291707	0.00852106	3.42337	0.0019
B versus dc	Linear model	Constant	-46.1278	5.65645	-8.15491	0.0000
		dc	14.2691	1.01735	14.0257	0.0000
	Quadratic model	Constant	-6.90073	2.99833	-2.30153	0.0290
		dc^2	1.24776	0.0899858	13.8662	0.0000
B versus h	Linear model	Constant	-19.9197	16.4361	-1.21195	0.2357
		h	5.82956	1.83216	3.18179	0.0036
	Quadratic model	Constant	3.65834	8.979379	0.407669	0.6866
		h^2	0.348094	0.106459	3.26973	0.0029

B: dry biomass (kg); dbh: diameter at breast height (cm); dc: crown diameter (m); h: total tree height (m)

It can be seen that there is a statistically significant relationship between the variables at the 95.0% confidence level for all analyzed regression models.

Table 21. Regression models to describe the relationship between the pruned biomass (B) and only one independent variable for *Morus alba*, park location

Residual biomass versus diameter at breast height (dbh)	
Type of equation	Equation
Linear	$B = 36.4781 + 0.968838 \cdot dbh$
Quadratic	$B = 60.7108 + 0.00858288 \cdot dbh^2$
Residual biomass versus crown diameter (dc)	
Type of equation	Equation
Linear	$B = -28.5302 + 12.2848 \cdot dc$
Quadratic	$B = 26.7134 + 0.652531 \cdot dc^2$
Residual biomass versus total tree height (h)	
Type of equation	Equation
Linear	$B = -168.767 + 25.8847 \cdot h$
Quadratic	$B = -46.3957 + 1.35979 \cdot h^2$

B: dry biomass (kg)

Table 22. Multiple regression analysis for *Morus alba*, park location

Residual biomass versus diameter at breast height (dbh)			
Type of equation	R^2	sd	MAE
Linear	0.18	27.13	20.43
Quadratic	0.11	28.14	21.20
Residual biomass versus crown diameter (dc)			
Type of equation	R^2	sd	MAE
Linear	0.59	18.99	14.02
Quadratic	0.60	18.90	14.23
Residual biomass versus total tree height (h)			
Type of equation	R^2	sd	MAE
Linear	0.47	21.68	17.77
Quadratic	0.48	21.55	17.69

R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error

Table 22 also indicates interdependence between residual biomass and crown diameter when annual maintenance pruning is carried out in parks although the coefficient of determination is lower than in topping (R^2=0.60 in the quadratic model). The P-values in the Table 23 are less than 0.05 indicating statistically significant relationship between the variables at the 95.0% confidence level. Only the P-value for the quadratic model of dbh exceeds this value.

Table 23. Significance of explicative variables for biomass prediction for *Morus alba*, park location

			Estimate	Standard error	T statistic	P-Value
B versus dbh	Linear model	Constant	36.4781	17.1883	2.12227	0.0428
		dbh	0.968838	0.389129	2.48976	0.0190
	Quadratic model	Constant	60.7108	10.0169	6.06086	0.0000
		dbh^2	0.00858288	0.00440714	1.9475	0.0616
B versus dc	Linear model	Constant	-28.5302	16.7584	-1.70245	0.0998
		dc	12.2848	1.90039	6.46435	0.0000
	Quadratic model	Constant	26.7134	8.51593	3.13687	0.0040
		dc^2	0.652531	0.100116	6.51775	0.0000
B versus h	Linear model	Constant	-168.767	48.8629	-3.45388	0.0018
		h	25.8847	5.11991	5.05569	0.0000
	Quadratic model	Constant	-46.3957	24.5075	-1.89312	0.0687
		h^2	1.35979	0.265579	5.12008	0.0000

B: dry biomass (kg); dbh: diameter at breast height (cm); dc: crown diameter (m); h: total tree height (m)

In addition, regression models for predicting residual biomass were tested from combinations of variables such us diameter at breast height, crown diameter and total tree height. The best results are shown in the tables below. A high R^2 value (R^2=0.96) was obtained for street location. The combination of these parameters improved the prediction model obtained from only the diameter at breast height. Also a high R^2 value was obtained for park location (R^2=0.88). This result improved the prediction models from one variable (Tables 24, 25, 26 and 27).

Table 24. Regression model to describe the relationship between residual biomass and dendrometric variables for *Morus alba*, street location

Biomass function*	R^2	sd	MAE
$B = 10.288 + 0.0256723 \cdot dbh^2 - 0.182728 \cdot dbh \cdot h - 3.18406 \cdot dc \cdot hc + 1.95276 \cdot h \cdot dc$	0.96	3.61	2.64

B: dry biomass (kg); R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error; dbh: diameter at breast height (cm); dc: crown diameter (m); hc: distance from soil to the crown (m); h: total tree height (m); * best equation validated with independent data

Table 25. Significance of explicative variables for biomass prediction for *Morus alba*, street location

Dependent variable: B
Independent variables: dbh^2, $dbh \cdot h$, $dc \cdot hc$, $h \cdot dc$

Parameter	Estimate	Standard error	T statistic	P-Value
Constant	10.288	7.00902	1.46783	0.1594
dbh^2	0.0256723	0.00478082	5.36984	0.0000
$dbh \cdot h$	-0.182728	0.0289018	-6.32238	0.0000
$dc \cdot hc$	-3.18406	0.795484	-4.00267	0.0008
$h \cdot dc$	1.95276	0.165387	11.8072	0.0000

B: dry biomass (kg); dbh: diameter at breast height (cm); dc: crown diameter (m); hc: distance from soil to the crown (m); h: total tree height (m)

Table 26. Regression model to describe the relationship between biomass and dendrometric variables for *Morus alba*, park location

Biomass function *	R^2	sd	MAE
$B = -1.8355 - 3.04043 \cdot dc \cdot h + 17.7895 \cdot dc \cdot hc + 1.87746 \cdot h^2 - 35.3771 \cdot hc^2$	0.88	11.52	7.68

B: dry biomass (kg); R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error; dc: crown diameter (m); hc: distance from soil to the crown (m); h: total tree height (m); * best equation validated with independent data

Table 27. Significance of regression model for biomass prediction for *Morus alba*, park location

Dependent variable: B Independent variables: dc·h, dc·hc, h^2, hc^2				
Parameter	Estimate	Standard error	T statistic	P-Value
Constant	-1.8355	20.2818	-0.0905	0.9289
dc·h	-3.04043	0.842644	-3.6082	0.0020
dc·hc	17.7895	3.90867	4.5513	0.0002
h^2	1.87746	0.427883	4.38779	0.0004
hc^2	-35.3771	8.43337	-4.1949	0.0005

B: dry biomass (kg); dc: crown diameter (m); hc: distance from soil to the crown (m); h: total tree height (m)

Prediction models for dried pruned biomass calculated from the apparent volume of the crown were also analyzed. As observed in Table 28, there is a good linear relationship between the conical and parabolic volume model and the amount of dry biomass yielded from topping pruning (R^2=0.90). This result could be expected, given that the apparent volume is calculated from combination from crown diameter and height. This indicates a good explanatory power for predicting biomass. A minor difference is observed in the hemispheric volume model (R^2=0.84).

Table 28. Regression model to describe the relationship between biomass and independent variable crown volume for *Morus alba*, street location

Type of model	Equation	R^2	sd	MAE
Conical volume model *	B = 2.65673 + 0.573367 · V cone	0.90	5.70	4.32
Parabolic volume model*	B = 2.65673 + 0.382245 · V paraboloid	0.90	5.70	4.32
Hemispheric volume model	B= 6.67744 + 0.524836 · V hemisphere	0.84	6.79	5.04

B: dry biomass (kg); R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error; * best equation validated with independent data

Since the conical and parabolic volume model are proportional and present the same coefficient of determination, the model with lower standard error, estimate and T statistic value is described below (Table 29).

Table 29. Significance of regression model for biomass prediction from crown volume for *Morus alba*, street location

Dependent variable: B Independent variable: V paraboloid				
Parameter	Estimate	Standard error	T statistic	P-Value
Constant	2.65673	2.38574	1.11359	0.2770
V paraboloid	0.382245	0.0263155	14.5254	0.0000

B: dry biomass (kg)

Table 30 shows that there is a lower relationship between the conical and parabolic volume model and the amount of dry biomass yielded from annual maintenance pruning (R^2=0.59).

Table 30. Regression model to describe the relationship between biomass and independent variable crown volume for *Morus alba*, park location

Type of model	Equation	R^2	sd	MAE
Conical volume model	B = 37.413 + 0.265421 · Vcone	0.59	19.03	14.42
Parabolic volume model	B = 37.413 + 0.176947 · Vparaboloid	0.59	19.03	14.42
Hemispheric volume model	B= 45.108 + 0.168542 · Vhemisphere	0.59	19.15	14.58

B: dry biomass (kg): R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error

The model with the lowest standard error, estimate and T statistic values is described below (Table 31).

Table 31. Significance of regression model for biomass prediction from crown volume for *Morus alba*, park location

Dependent variable: B				
Independent variables: V paraboloid				
Parameter	Estimate	Standard error	T statistic	P-Value
Constant	37.413	7.12473	5.25115	0.0000
V paraboloid	0.176947	0.0274815	6.43878	0.0000

B: dry biomass (kg)

The park location sample was bigger according to all dendrometric variables and yielded higher quantities of biomass. Reasons exist to believe that the quantity of residual biomass depends not only on tree dimensions but is also strongly correlated with type of pruning practice applied. Where, the type of pruning practice applied, depends on the location of the tree and all functions and limits related to it (Michau, 1987, Gil-Albert, 201, Drenou, 2006).

A high relationship between crown diameter (R^2=0.87) as well as apparent crown volume (R^2=0.90) and dry biomass were observed for topping type of pruning practice and street location. This is explained by the characteristics of the pruning operation, where practically a major part of the canopy is being removed from the tree, leaving mostly branch stubs (Michau, 1987). This results in significant reduction of crown volume.

In case of annual maintenance type of pruning, there is no clear interdependence between lonely parameters and quantity of dry biomass. The best result is found between crown diameter and yielded residual biomass in quadratic model (R^2=0.60). For this, a combination of parameters was tested, what led to an improved result (R^2=0.88). This may be explained by the characteristics of the pruning practice, were both tree height and crown diameters are reduced in a rather equal way (Michau, 1987). Annual maintenance type of pruning leads to the elimination of annual branches. Therefore, the total tree height and crown diameter are affected, but not as strongly as in topping type of pruning. It is important to mention, that the diameter at breast height does not present high interdependence with the obtained biomass (R^2=0.18). This means that the incensement of age, and therefore quantity of branched in older trees does not influence the quantity of biomass. This may be caused due to the high vigour of young trees. This fact shows a clear difference with the trees from forest systems.

5.1.2. *Platanus hispanica*

The variable analysis results are presented in Table 32. The analysis indicates that the standardized skewness and kurtosis values are within the range expected for data from a normal distribution and P-values of the Shapiro Wilks test are higher than 0.05. The tree-sample includes individuals with small to large canopies and heights. Compared sample trees of *Platanus hispanica* are characterized with mean diameter at breast height 23.56 cm, mean crown diameter 8.44 m, mean distance from soil to the crown 3.76 m and mean total height 11.57 m. 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 biomass for all sample trees were 23.98 kg and 15.16 kg respectively.

Table 32. Variable analysis of *Platanus hispanica* trees

Variable	Average	Standard deviation	Standard skewness	Standard kurtosis	Shapiro Wilks test (P-value)	Maximum	Minimum
Diameter at breast height (cm)	23.56	7.92	1.12	0.56	0.303	45.50	11.20
Crown diameter (m)	8.44	2.41	0.37	-0.86	0.778	13.30	4.10
Total tree height (m)	11.57	2.38	0.55	0.26	0.795	17.00	6.40

a) Branch form factor and volume functions

Table 33 shows the results of mean and standard deviation values of the branch form factors obtained from different models for *Platanus hispanica*. The model that produced a form factor closest to 1 was the cylinder. This model represented the best fit to characterize the actual volume.

Table 33. Mean and standard deviation of form factor of sample branches of *Platanus hispanica*

	Real volume					
Model volume	Huber		Newton		Smalian	
	f	sd f	f	sd f	f	sd f
Cylinder	0.72	0.11	0.72	0.11	0.71	0.11
Paraboloid	1.45	0.23	1.44	0.23	1.43	0.22
Cone	2.18	0.35	2.17	0.34	2.14	0.34
Neiloid	2.91	0.47	2.89	0.46	2.86	0.45

f : mean form factor; sdf : standard deviation of form factor

The variation of the form factor from the base diameter and length of the branches was studied by means of regression models. The coefficients of determination, standard deviation and mean absolute error are presented in Table 34.

Table 34. Regression model to describe the relationship between f and 2 independent variables do, h in branches of *Platanus hispanica*

Equation	R^2	sd	MAE
$f = 0.878299 + 0.0996161 \cdot do - 0.00478805 \cdot l$	0.50	0.08	0.07

f: form factor; R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error; do: base diameter of a branch (cm); l: length of a branch (cm)

The low values of R^2 can indicate that the model for form factor calculation explains poorly its variability. Therefore, if this technique is used to calculate the volume, the mean must be used.

Table 35. Significance of explicative variables for form factor for *Platanus hispanica*

Dependent variable: f cylinder
Independent variables: do, l

Parameter	Estimate	Standard error	T statistic	P-Value
Constant	0.878299	0.0878208	10.001	0.0000
do	0.0996161	0.0307073	3.24405	0.0059
l	-0.00478805	0.00141765	3.37745	0.0045

f: form factor; do: base diameter of a branch (cm); l: length of a branch (cm)

On the other hand, Table 36 shows the results of adjusting the volume functions for *Platanus hispanica* branches. For each model, were obtained the coefficient of determination, standard deviation and mean absolute error.

Table 36. Branch volume functions for *Platanus hispanica*

Author	Volume function	R^2	sd	MAE
Naslund (modif)	$V = -0.96235 + 3.02575 \cdot do^2 + 0.681096 \cdot do^2 \cdot l - 0.00375207 \cdot do \cdot l^2$	0.99	21.63	13.50
Spurr *	$V = -11.2731 + 0.620237 \cdot do^2 \cdot l$	0.99	27.14	19.13
Ogaya	$V = -21.0495 + 15.4334 \cdot do^2 + 0.457927 \cdot do^2 \cdot l$	0.99	22.39	15.74
Hoenald-Krenn	$V = 56.5386 - 106.076 \cdot do + 80.7595 \cdot do^2$	0.97	36.95	25.20

R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error; V: volume of a branch (cm^3); do: base diameter of a branch (cm); l: length of a branch (cm); * best equation validated with independent data

The coefficients of determination (R^2) for all the analyzed models were high. Although Naslund equation had the highest R^2 value, all its explicative variables were not significant. The volume function that presented the lowest P-values in its variables was Spurr. Table 37 presents a detailed statistical analysis of the selected volume functions.

Table 37. Significance of explicative variables for Spurr volume function for *Platanus hispanica* branches

Dependent variable: V
Independent variables: $do^2 \cdot l$

Parameter	Estimate	Standard error	T statistic	P-Value
Constant	-11.2731	11.6888	-0.964431	0.3576
$do^2 \cdot l$	0.620237	0.0201921	30.7167	0.0000

V: volume of a branch (cm^3); do: base diameter of a branch (cm); l: length of a branch (cm)

The P-value is less than 0.05. There is a statistically significant relationship between the variables at the 95.0% confidence level.

b) Regression models for biomass prediction

Following regression models were calculated to predict the amount of residual biomass from crown raising pruning operations of *Platanus hispanica* from simple measures such as diameter at breast height, crown diameter and total tree height (Table 38 and 39).

Table 38. Regression models to describe the relationship between the pruned biomass (B) and only one independent variable for *Platanus hispanica*

Residual biomass versus diameter at breast height (dbh)	
Type of equation	Equation
Linear	$B = -16,4074 + 1,71395 \cdot dbh$
Quadratic	$B = 2,83173 + 0,0343369 \cdot dbh^2$
Residual biomass versus crown diameter (dc)	
Type of equation	Equation
Linear	$B = -18,6037 + 5,04282 \cdot dc$
Quadratic	$B = 1,03702 + 0,298084 \cdot dc^2$
Residual biomass versus total tree height (h)	
Type of equation	Equation
Linear	$B = -31,7936 + 4,81816 \cdot h$
Quadratic	$B = -5,1046 + 0,208479 \cdot h^2$

B: dry biomass (kg)

Table 39. Multiple regression analysis for *Platanus hispanica*

Residual biomass versus diameter at breast height (dbh)			
Type of equation	R^2	sd	MAE
Linear	0.80	6.88	5.11
Quadratic	0.87	5.55	4.30
Residual biomass versus crown diameter (dc)			
Type of equation	R^2	sd	MAE
Linear	0.64	9.17	6.43
Quadratic	0.68	8.60	6.02
Residual biomass versus total tree height (h)			
Type of equation	R^2	sd	MAE
Linear	0.57	10.06	7.20
Quadratic	0.61	9.55	7.18

R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error

The results in Table 39 indicate, that there is a high interdependence between residual biomass and diameter at breast height with a coefficient of determination at the level $R^2 = 0.87$ in the quadratic model. This indicates a good explanatory power for predicting biomass. There is also an interdependence between the residual biomass and crown diameter at the level $R^2 = 0.68$ in the quadratic model.

Table 40. Significance of explicative variables for biomass prediction of *Platanus hispanica*

			Estimate	Standard error	T statistic	P-Value
B versus dbh	Linear model	Constant	-16.4074	4.00646	-4.09525	0.0003
		dbh	1.71395	0.16142	10.618	0.0000
	Quadratic model	Constant	2.83173	1.84457	1.53517	0.1360
		dbh^2	0.0343369	0.00250148	13.7266	0.0000
B versus dc	Linear model	Constant	-18.6037	6.17453	-3.01298	0.0054
		dc	5.04282	0.703727	7.16588	0.0000
	Quadratic model	Constant	1.03702	3.30936	0.31336	0.7563
		dc^2	0.298084	0.0378327	7.879	0.0000
B versus h	Linear model	Constant	-31.7936	9.24295	-3.43977	0.0018
		h	4.81816	0.782486	6.1575	0.0000
	Quadratic model	Constant	-5.1046	4.6728	-1.09241	0.2840
		h^2	0.208479	0.0310664	6.71078	0.0000

B: dry biomass (kg); dbh: diameter at breast height (cm); dc: crown diameter (m); h: total tree height (m)

The P-values in Table 40 are less than 0.05. This indicates that there is a statistically significant relationship between the variables at the 95.0% confidence level.

In addition, regression models for predicting residual biomass were tested from combinations of variables such us diameter at breast height, crown diameter and total tree height. The best result is shown in the Table 41 and 42. Although a high R^2 value (R= 0.93) was obtained, the combination of these parameters did not improve significantly the prediction model obtained from only the diameter at breast height.

Table 41. Regression model to describe the relationship between biomass and dendrometric variables for *Platanus hispanica*

Equation*	R^2	sd	MAE
$B = 3.3003 + 0.270102 \cdot dc \cdot dbh - 0.500268 \cdot dc^2$	0.93	4.52	3.32

R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error; dbh: diameter at breast height (cm); dc: crown diameter (m); * best equation validated with independent data

Table 42. Significance of explicative variables for biomass prediction for *Platanus hispanica*

Dependent variable: B
Independent variables: dc^2 , $dbh \cdot dc$

Parameter	Estimate	Standard error	T statistic	P-Value
Constant	3.3003	1.99139	1.65729	0.1131
dc^2	-0.500268	0.110639	-4.52161	0.0002
$dbh \cdot dc$	0.270102	0.0352703	7.65807	0.0000

B: dry biomass (kg); dbh: diameter at breast height (cm); dc: crown diameter (m)

Below are presented the prediction models calculated from the apparent volume of the crown. As observed in Table 43 there is a good linear relationship between the conical and parabolic volume model and the amount of dry biomass yielded from pruning (R^2=0.78). A minor difference is observed in the hemispheric volume model (R^2=0.71).

Table 43. Regression model to describe the relationship between biomass and independent variable crown volume for *Platanus hispanica*

Type of model	Equation	R^2	sd	MAE
Conical volume model *	B = 6.10934 + 0.0992547·Vcone	0.78	7.62	5.30
Parabolic volume model	B = 6.10934 + 0.0661698·Vparaboloid	0.78	7.62	5.30
Hemispheric volume model	B = 7.8498 + 0.0824432·Vhemisphere	0.71	8.29	6.17

B: dry biomass (kg); R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error; * best equation validated with independent data

The model with the lowest standard error, estimate and T statistic values is described below (Table 44).

Table 44. Significance of explicative variables for residual biomass prediction for *Platanus hispanica*

Dependent variable: B
Independent variables: V paraboloid

Parameter	Estimate	Standard error	T statistic	P-Value
Constant	6.10934	2.5908	2.35809	0.0272
V paraboloid	0.0661698	0.00725681	9.11831	0.0000

B: dry biomass (kg)

The high interdependence between the quantity of pruned biomass and diameter at breast height (R^2 =0.87) is probably the result of the pruning practice applied. The crown raising type of pruning is highly dependent from the age of the tree as it is used to give a tree a particular form. It is important to mention that crown raising is introduced in young trees, that have very thin branches (Michau, 1987). When the tree is older, the lower branches are thicker, therefore probably the residual biomass obtained by this pruning type in bigger, as shown by the positive coefficient of the dhb in the Table 39.

The relationship between biomass and crown diameter (R^2 =0.68) can be explained by the fact that crown raising is based on removing the lower braches which are in many cases the oldest and widest ones. Nevertheless, it is important to point that the lower branches do not receive as much light as in the top when the crown is fully developed and therefore these branches will grow more slowly, leading to lack of pruning after a certain age of the tree or to less frequency.

5.1.3. ***Sophora japonica***

The variable analysis results are presented in Table 45. The sample includes rather young trees. It can be observed that the variables follow a normal distribution (Shapiro-Wilks test P-value > 0.05).

Table 45. Variable analysis for *Sophora japonica* trees

Variable	Average	Standard deviation	Standard skewness	Standard kurtosis	Shapiro-Wilks test (P-value)	Maximum	Minimum
Diameter at breast height (cm)	17.80	2.39	1.00	-0.45	0.317	23.00	13.80
Crown diameter (m)	6.95	0.98	1.72	0.98	0.225	9.75	5.35
Total tree height (m)	10.22	1.10	-0.09	0.04	0.684	12.40	7.60

Sample trees of *Sophora japonica* are characterized with mean diameter at breast height 17.80 cm, mean crown diameter 6.95 m, mean distance from soil to the crown 3.53 m and mean total height 10.2 2m. Wood formed 59.97% of total weight of all pruned material before drying while the rest 40.03% belonged to leaves. Wood moisture content was 44.88% in wet basis. The mean and standard deviation of residual biomass for all sample trees were 18.07 kg and 4.25 kg, respectively.

a) Branch form factor and volume functions

Table 46 shows the results of mean and standard deviation values of the branch form factors obtained for different models. The model that produced a form factor closest to 1 was the paraboloid. This model represented the best fit to characterize the actual shape.

Table 46. Mean and standard deviation of form factor of sample branches of *Sophora japonica*

	Real volume					
Model volume	Huber		Newton		Smalian	
	f	sd f	f	sd f	f	sd f
Cylinder	0.58	0.10	0.58	0.09	0.57	0.09
Paraboloid	1.16	0.20	1.16	0.19	1.15	0.18
Cone	1.74	0.30	1.74	0.29	1.72	0.27
Neiloid	2.32	0.40	2.32	0.38	2.30	0.36

f: mean form factor; sdf :standard deviation of form factor

The variation of the form factor from the base diameter and length of the branches was studied by means of regression models. The coefficients of determination, standard deviation and mean absolute error are presented in Table 47.

Table 47. Regression model to describe the relationship between f and 2 independent variables do, h in branches of *Sophora japonica*

Form factor function	R^2	sd	MAE
$f = 0.908292 – 0.199766 \cdot do – 0.000713573 \cdot l$	0.20	0.09	0.07

f: form factor; R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error; do: base diameter of a branch (cm); l: length of a branch (cm)

P-values are greater than 0.05 can indicate that the form factor is not dependent of these variables (Table 48). There is not a statistically significant relationship between the variables at the 95.0% or higher confidence level. Therefore, the mean must be used for volume calculation.

Table 48. Significance of explicative variables for form factor for *Sophora japonica*

Dependent variable: f cylinder Independent variables: do, l				
Parameter	Estimate	Standard error	T statistic	P-Value
Constant	0.908292	0.191433	4.74471	0.0004
do	-0.199766	0.131484	-1.51932	0.1526
l	-0.000713573	0.00110003	-0.648684	0.5278

f: form factor; do: base diameter of a branch (cm); l: length of a branch (cm)

Table 49 shows the results of adjusting the volume functions for *Sophora japonica* branches. For each model, were obtained the coefficient of determination, standard deviation and mean absolute error.

Table 49. Branch volume functions for *Sophora japonica*

Author	Volume function	R^2	sd	MAE
Naslund (modif)	$V = -51.7828 + 149.11 \cdot do^2 – 1.16356 \cdot do^2 \cdot l + 0.00673976 \cdot do \cdot l^2$	0.86	12.03	8.31
Spurr *	$V = 23.6538 + 0.313124 \cdot do^2 \cdot l$	0.71	5.12	12.27
Ogaya	$V = 12.7026 + 9.5878 \cdot do^2 + 0.305009 \cdot do^2 \cdot l$	0.80	13.80	10.48
Hoenald-Krenn	$V = -15.6948 + 44.1069 \cdot do + 35.16 \cdot do^2$	0.68	17.68	13.21

R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error; V: volume of a branch (cm^3); do: base diameter of a branch (cm); l: length of a branch (cm); * best equation validated with independent data

The coefficients of determination for all the analyzed models were high. The volume function that presented the lowest P-values was the Spurr. Table 50 presents a detailed statistical analysis of the selected volume functions.

Table 50. Significance of explicative variables for Spurr volume function for *Sophora japonica* branches

Dependent variable: V Independent variables: $do^2 \cdot l$				
Parameter	Estimate	Standard error	T statistic	P-Value
Constant	23.6538	12.9521	1.82625	0.1011
$do^2 \cdot l$	0.313124	0.0665157	4.70752	0.0011

V: volume of a branch (cm^3); do: base diameter of a branch (cm); l: length of a branch (cm)

The P-value is less than 0.05, for that there is a statistically significant relationship between the variables at the 95.0% confidence level.

b) Regression models for biomass prediction

Regression models were calculated to predict the amount of residual biomass from topping operations of *Sophora japonica* from simple measures such as diameter at breast height, crown diameter and total tree height (Table 51).

Table 51. Regression models to describe the relationship between the pruned biomass (B) and only one independent variable for *Sophora japonica*

Residual biomass versus diameter at breast height (dbh)	
Type of equation	Equation
Linear	$B = -6.01363 + 1.35314 \cdot dbh$
Quadratic	$B = 6.39409 + 0.036227 \cdot dbh^2$
Residual biomass versus crown diameter (dc)	
Type of equation	Equation
Linear	$B = 1.83398 + 2.33671 \cdot dc$
Quadratic	$B = 10.1679 + 0.160592 \cdot dc^2$
Residual biomass versus total tree height (h)	
Type of equation	Equation
Linear	$B = 2.53502 + 1.51976 \cdot h$
Quadratic	$B = 9.99374 + 0.0764211 \cdot h^2$

B: dry biomass (kg)

Table 52. Multiple regression analysis for *Sophora japonica*

Residual biomass versus diameter at breast height (dbh)			
Type of equation	R^2	sd	MAE
Linear	0.57	2.80	2.28
Quadratic	0.55	2.87	2.33
Residual biomass versus crown diameter (dc)			
Type of equation	R^2	sd	MAE
Linear	0.29	3.64	2.86
Quadratic	0.29	3.63	2.81
Residual biomass versus total tree height (h)			
Type of equation	R^2	sd	MAE
Linear	0.15	3.97	3.04
Quadratic	0.16	3.94	3.04

R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error

The results in the Table 52 indicate that there is an interdependence between residual biomass and diameter at breast height with a coefficient of determination at the level R^2=0.57 in the linear model.

Table 53. Significance of explicative variables for biomass prediction of *Sophora japonica*

			Estimate	Standard error	T statistic	P-Value
B versus dbh	Linear model	Constant	-6.01363	3.91471	-1.53616	0.1357
		dbh	1.35314	0.218015	6.20665	0.0000
	Quadratic model	Constant	6.39409	2.02861	3.15196	0.0038
		dbh^2	0.036227	0.00607795	5.9604	0.0000
B versus dc	Linear model	Constant	1.83398	4.84315	0.378674	0.7078
		dc	2.33671	0.690234	3.3854	0.0021
	Quadratic model	Constant	10.1679	2.4023	4.23259	0.0002
		dc^2	0.160592	0.046898	3.42428	0.0019
B versus h	Linear model	Constant	2.53502	6.83493	0.370891	0.7135
		h	1.51976	0.664682	2.28644	0.0300
	Quadratic model	Constant	9.99374	3.49134	2.86243	0.0079
		h^2	0.0764211	0.0323063	2.36552	0.0252

B: dry biomass (kg); dbh: diameter at breast height (cm); dc: crown diameter (m); h: total tree height (m)

The P-values in the Table 53 are less than 0.05. This indicates that there is a statistically significant relationship between the variables at the 95.0% confidence level.

In addition, to improve the regression models for predicting residual biomass, combinations of variables such us diameter at breast height, crown diameter and total tree height were tested. The best result is shown in Table 54 and 55. A high R^2 value (R=0.76) was obtained, so the combination of these parameters improved significantly the prediction model obtained from only the diameter at breast height.

Table 54. Regression model to describe the relationship between B and dendrometic variables for *Sophora japonica*

Equation *	R^2	sd	MAE
$B = 11.3625 - 0.871214 \cdot hc \cdot h + 0.213012 \cdot hc \cdot dbh + 0.168353 \cdot h^2 + 0.0274955 \cdot hc \cdot h \cdot dc$	0.76	2.08	1.52

B: dry biomass (kg); R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error; dbh: diameter at breast height (cm); hc: distance from soil to the crown (m); h: total tree height (m); * best equation validated with independent data

Table 55. Significance of explicative variables for biomass prediction for *Sophora japonica*

Dependent variable: B
Independent variables: $hc \cdot h$, $hc \cdot dbh$, h^2, $hc \cdot h \cdot dc$

Parameter	Estimate	Standard error	T statistic	P-Value
Constant	11.3625	3.61503	3.14312	0.0059
$hc \cdot h$	-0.871214	0.135502	-6.42953	0.0000
$hc \cdot dbh$	0.213012	0.0801992	2.65603	0.0166
h^2	0.168353	0.0366845	4.58923	0.0003
$hc \cdot h \cdot dc$	0.0274955	0.0126113	2.18023	0.0436

B: dry biomass (kg); dbh: diameter at breast height (cm); dc: crown diameter (m); hc: distance from soil to the crown (m); h: total tree height (m)

Next, prediction models calculated from the apparent volume of the crown were analyzed. As observed in Table 56, there is a low relationship between the conical and parabolic volume model and the amount of dry biomass obtained from pruning (R^2=0.37). This fact could be due to the hard pruning practiced in the crown. This can be seen in trees of figures 9 and 10, where only the main branches were not pruned. The hard pruning influences the crown volume each year. Therefore the prediction equations did not involve good statistical parameters. A minor difference is observed in the hemispheric volume model (R^2=0.29). Conical and parabolic volume model present the same coefficient of determination because they are proportional (Table 56). P-values are less than 0.05, therefore there is a statistically significant relationship between the variables at the 95.0% confidence level (Table 57).

Table 56. Regression model to describe the relationship between biomass and independent variable crown volume for *Sophora japonica*

Type of model	Equation	R^2	sd	MAE
Conical volume model	B = 11.0513 + 0.0805709· V cone	0.37	3.41	2.64
Parabolic volume model	B = 11.0513 + 0.0537139· V paraboloid	0.37	3.41	2.64
Hemispheric volume model	B = 13.0227 + 0.0542687· V hemisphere	0.29	3.63	2.78

B: dry biomass (kg); R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error

Table 57. Significance of explicative variables for biomass prediction for *Sophora japonica*

Dependent variable: B
Independent variables: V paraboloid

Parameter	Estimate	Standard error	T statistic	P-Value
Constant	11.0513	1.81309	6.0953	0.0000
V paraboloid	0.0537139	0.0130225	4.12471	0.0003

B: dry biomass (kg)

An interdependence between diameter at breast height and dry residual biomass (R^2 =0.57) was observed for topping type of pruning practice. This indicates that the species produces more biomass with age. This may be caused, due to the fact that older trees have more and thicker branches in the crown. The best prediction model was given with the combination of several dendrometric variables, such as total height, crown height, crown diameter and diameter at breast height (R^2=0.76).

5.1.4. *Phoenix canariensis*

The variable analysis results are presented in Table 58. It can be observed that the values are within the range expected for data from a normal distribution.

Table 58. Variable analysis of *Phoenix canariensis* trees

Variable	Average	Standard deviation	Standard skewness	Standard kurtosis	Shapiro-Wilks test (P-value)	Maximum	Minimum
Diameter at breast height (cm)	68.23	8.66	1.95	1.40	0.053	90.80	54.50
Crown diameter (m)	7.00	0.70	-0.93	1.40	0.345	8.40	5.00
Total tree height (m)	7.78	1.40	-1.74	-0.03	0.071	9.70	4.60

The *Phoenix canariensis* sampled trees are characterized with mean diameter at breast height 68.23 cm, mean crown diameter 7.00 m, mean distance from soil to the crown 3.58 m and mean total height 7.78 m. A number of 962 palm fronds were examined. The palm fronds are characterized with mean length 3.86 m and mean weight of green frond 3.35 kg. The average number of cut fronds per tree was 32.06. Wood moisture content was measured in 3 parts of the frond (lower, middle and upper section). Mean wood moisture content was 74.82% in wet basis. The mean and standard deviation of biomass for all sample trees were 24.67 kg and 7.82 kg respectively.

a) Regression models for biomass prediction

Several regression models were calculated to predict the amount of residual biomass from annual pruning operations of *Phoenix canariensis* from simple measures such as diameter at breast height, crown diameter and total tree height. The R^2 in the Table 59 indicate that there is no interdependence between residual biomass and any lonely dendrometric variable. Nevertheless the R^2 reaches 0.88 when several variables are examined together. Tables 59, 60 and 61 show the results for annual pruning of this species.

Table 59. Regression models to describe the relationship between the pruned biomass (B) and only one independent variable for *Phoenix canariensis*

Residual biomass versus diameter at breast height (dbh)	
Type of equation	Equation
Linear	$B = 35.0669 – 0.119591 \cdot dbh$
Quadratic	$B = 31.8727 – 0.00105024 \cdot dbh^2$
Residual biomass versus crown diameter (dc)	
Type of equation	Equation
Linear	$B = -1.50216 + 4.05595 \cdot dc$
Quadratic	$B = 13.0844 + 0.278992 \cdot dc^2$
Residual biomass versus total tree height (h)	
Type of equation	Equation
Linear	$B = 1.6853 + 3.23786 \cdot h$
Quadratic	$B = 12.8137 + 0.225234 \cdot h^2$

B: dry biomass (kg)

Table 60. Multiple regression analysis for *Phoenix canariensis*

Residual biomass versus diameter at breast height (dbh)			
Type of equation	R^2	sd	MAE
Linear	0.01	7.90	5.95
Quadratic	0.02	7.86	5.92
Residual biomass versus crown diameter (dc)			
Type of equation	R^2	sd	MAE
Linear	0.13	7.41	5.75
Quadratic	0.12	7.47	5.83
Residual biomass versus total tree height (h)			
Type of equation	R^2	sd	MAE
Linear	0.33	6.49	5.03
Quadratic	0.34	6.44	4.96

R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error

Table 61 shows that some P-values are greater or 0.05. These variables are not statistically significant at the 95.0% confidence level.

Table 61. Significance of explicative variables for biomass prediction of *Phoenix canariensis*

			Estimate	Standard error	T statistic	P-Value
B versus dbh	Linear model	Constant	35.0669	11.8485	2.95962	0.0063
		dbh	-0.119591	0.172315	-0.694025	0.4936
	Quadratic model	Constant	31.8727	5.80661	5.48903	0.0000
		dbh^2	-0.00105024	0.0011887	-0.883523	0.3848
B versus dc	Linear model	Constant	-1.50216	13.9265	-0.107864	0.9149
		dc	4.05595	1.97852	2.04999	0.0502
	Quadratic model	Constant	13.0844	7.30539	1.79105	0.0845
		dc^2	0.278992	0.144762	1.92724	0.0645
B versus h	Linear model	Constant	1.6853	6.93872	0.242883	0.8099
		h	3.23786	0.877181	3.69121	0.0010
	Quadratic model	Constant	12.8137	3.90688	3.27979	0.0029
		h^2	0.225234	0.0594392	3.78933	0.0008

B: dry biomass (kg); dbh: diameter at breast height (cm); dc: crown diameter (m); h: total tree height (m)

In addition, regression models for predicting residual biomass were tested from combinations of variables such as diameter at breast height, crown diameter and total tree height. The best result is shown in the tables below. A high R^2 value (R^2=0.88) was obtained. There is a statistically significant relationship between the variables at the 95.0% confidence level. The combination of these parameters improved the prediction models obtained from only one variable (Tables 62 and 63).

Table 62. Regression model to describe the relationship between residual biomass and dendrometric variables for *Phoenix canariensis*

Equation *	R^2	sd	MAE
B = -483.752 + 145.266 · dc - 36.1174 · h + 56.9057 · hc - 0.395022 · dbh · dc + 0.840297 · dbh · h - 0.896813 · dbh · hc - 4.74705 dc^2 - 6.50947 · dc · h + 8.45532 · h · hc - 8.75568 · hc^2	0.88	4.09	2.04

B: dry biomass (kg); R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error; dbh: diameter at breast height (cm); dc: crown diameter (m); hc: distance from soil to the crown (m); h: total tree height (m); * best equation validated with independent data

Table 63. Significance of explicative variables for biomass prediction for *Phoenix canariensis*

Dependent variable: B
Independent varable: dc, h, hc, dbh · hc, dbh · h , dbh · hc, dc^2, dc · h, h · hc, hc^2

Parameter	Estimate	Standard error	T statistic	P-Value
Constant	-483.752	103.32	-4.68209	0.0004
dc	145.266	29.943	4.85142	0.0003
h	-36.1174	9.53202	-3.78906	0.0023
hc	56.9057	12.9054	4.40945	0.0007
dbh · hc	-0.395022	0.0931535	-4.24055	0.0010
dbh · h	0.840297	0.169924	4.94513	0.0003
dbh · hc	-0.896813	0.19612	-4.57278	0.0005
dc^2	-4.74705	1.39458	-3.40392	0.0047
dc · h	-6.50947	1.33858	-4.86298	0.0003
h · hc	8.45532	2.22375	3.80227	0.0022
hc^2	-8.75568	2.39799	-3.65126	0.0029

B: dry biomass (kg); dbh: diameter at breast height (cm); dc: crown diameter (m); hc: distance from soil to the crown (m); h: total tree height (m)

Prediction models calculated from the apparent volume of the crown were also analyzed. As observed in Table 64, there is no relationship between the crown volume model and the amount of dry biomass obtained from pruning.

Table 64. Regression model to describe the relationship between biomass and independent variable crown volume for *Phoenix canariensis*

Type of model	Equation	R^2	sd	MAE
Conical volume model	B = 16.4062 + 0.195602 · V cone	0.16	7.30	5.86
Parabolic volume model	B = 16.4062 + 0.130401 · V paraboloid	0.16	7.30	5.86
Hemispheric volume model	B = 18.1107 + 0.0950477 · V hemisphere	0.10	7.53	5.88

B: dry biomass (kg); R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error

The model with the lowest standard error, estimate and T statistic values is described below (Table 65)

Table 65. Significance of explicative variables for biomass prediction for *Phoenix canariensis*

Dependent variable: B Independent variable: V paraboloid				
Parameter	Estimate	Standard error	T statistic	P-Value
Constant	16.4062	4.82243	3.40207	0.0021
V paraboloid	0.130401	0.0574664	2.26917	0.0315

B: dry biomass (kg)

5.1.5. ***Phoenix dactilifera***

Table 66 shows the variable analysis which indicates that the standardized skewness and kurtosis values are within the range expected for data from a normal distribution.

Table 66. Variable analysis of *Phoenix dactilifera* trees

Variable	Average	Standard deviation	Standard skewness	Standard kurtosis	Shapiro-Wilks test (P-value)	Maximum	Minimum
Diameter at breast height (cm)	43.96	6.79	0.94	-0.34	0.202	60.00	33.25
Crown diameter (m)	7.49	1.24	-0.42	1.70	0.053	10.32	4.41
Total tree height (m)	9.97	3.32	1.27	-0.25	0.267	17.30	4.60

Analysed sample trees of *Phoenix dactilifera* are characterized with mean diameter at breast height 43.96 cm, mean crown diameter 7.49 m, mean distance from soil to the crown 5.69 m and mean total height 9.97 m. A number of 1309 palm fronds were examined. The palm fronds are characterized with mean length 3.83m and mean weight of green frond 2.68 kg. The average number of cut fronds per tree was 46.75. Wood moisture content was measured in 3 parts of the frond (lower, middle and upper section). Mean wood moisture content was 71.03% in wet basis. The mean and standard deviation of biomass for all sample trees were 36.13 kg and 11.37 kg respectively.

a) Regression models for biomass prediction

Following regression models were calculated to predict the amount of residual biomass from annual pruning operations of *Phoenix dactilifera* from simple measures such as diameter at breast height, crown diameter and total tree height (Table 67).

Table 67. Regression models to describe the relationship between the pruned biomass (B) and only one independent variable for *Phoenix dactilifera*

Residual biomass versus diameter at breast height (dbh)	
Type of equation	Equation
Linear	$B = 36.6599 – 0.011933 \cdot dbh$
Quadratic	$B = 36,7375 - 0,000304493 \cdot dbh^2$
Residual biomass versus crown diameter (dc)	
Type of equation	Equation
Linear	$B = 17.6568 + 2.46572 \cdot dc$
Quadratic	$B = 27.0116 + 0.15821 \cdot dc^2$
Resisual biomass versus total tree height (h)	
Type of equation	Equation
Linear	$B = 30.6891 + 0.545904 \cdot h$
Quadratic	$B = 32.9225 + 0.0291616 \cdot h^2$

B: dry biomass (kg)

Table 68. Multiple regression analysis for *Phoenix dactilifera*

Resisual biomass versus diameter at breast height (dbh)			
Type of equation	R^2	sd	MAE
Linear	0.00	11.59	9.23
Quadratic	0.00	11.58	9.22
Resisual biomass versus crown diameter (dc)			
Type of equation	R^2	sd	MAE
Linear	0.07	11.15	8.55
Quadratic	0.06	11.19	8.57
Resisual biomass versus total tree height (h)			
Type of equation	R^2	sd	MAE
Linear	0.02	11.44	9.04
Quadratic	0.03	11.38	8.99

R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error

The low R^2 in Table 68 indicate that there is no interdependence between residual biomass and any of the examined variables.

Table 69. Significance of explicative variables for biomass prediction of *Phoenix dactilifera*

			Estimate	Standard error	T statistic	P-Value
B versus dbh	Linear model	Constant	36.6599	14.6076	2.50965	0.0186
		dbh	-0.011933	0.328467	-0.0363294	0.9713
	Quadratic model	Constant	36.7375	7.46454	4.9216	0.0000
		dbh^2	-0.000304493	0.00360809	-0.0843919	0.9334
B versus dc	Linear model	Constant	17.6568	13.0508	1.35292	0.1877
		dc	2.46572	1.71858	1.43474	0.1633
	Quadratic model	Constant	27.0116	6.99324	3.86254	0.0007
		dc^2	0.15821	0.115585	1.36877	0.1828
B versus h	Linear model	Constant	30.6891	6.95883	4.41009	0.0002
		h	0.545904	0.66299	0.823396	0.4178
	Quadratic model	Constant	32.9225	3.93154	0.37396	0.0000
		h^2	0.0291616	0.0298689	0.976321	0.3379

B: dry biomass (kg); dbh: diameter at breast height (cm); dc: crown diameter (m); h: total tree height (m)

The P-values in Table 69 are greater or 0.05. There is not a statistically significant relationship between the variables at the 95.0% or higher confidence level.

In addition, regression models for predicting residual biomass were tested from combinations of variables such us diameter at breast height, crown diameter and total tree height. The best result is shown in the Table 70 and 71. A higher R^2 value (R^2=0.67) was obtained. The combination of these parameters improved the prediction models obtained from one variable.

Table 70. Regression model to describe the relationship between residual biomass and dendrometric variables for *Phoenix dactilifera*

Equation *	R^2	sd	MAE
$B = 64.4552 - 19.651 \cdot h + 20.2859 \cdot hc + 1.70061 \cdot h^2 - 2.08599 \cdot h \cdot hc$	0.67	6.00	4.01

B: dry biomass (kg); R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error; hc: distance from soil to the crown (m); h: total tree height (m); * best equation validated with independent data

Table 71. Significance of explicative variables for biomass prediction for *Phoenix dactilifera*

Dependent variable: B
Independent varable: h. hc, h^2, $h \cdot hc$

Parameter	Estimate	Standard error	T statistic	P-Value
Constant	64.4552	19.137	3.36809	0.0039
h	-19.651	6.43542	-3.05357	0.0076
hc	20.2859	5.97769	3.3936	0.0037
h^2	1.70061	0.462525	3.6768	0.0020
$h \cdot hc$	-2.08599	0.54423	-3.83293	0.0015

B: dry biomass (kg); hc: distance from soil to the crown (m); h: total tree height (m)

The P-values are less than 0.05, for that there is a statistically significant relationship between the variables at the 95.0% confidence level.

Prediction models calculated from the apparent volume of the crown were analyzed. As observed in Table 72, there is no relationship between the crown volume model and the amount of dry biomass obtained from pruning.

Table 72. Regression model to describe the relationship between biomass and independent variable crown volume for *Phoenix dactilifera*

Type of model	Equation	R^2	sd	MAE
Conical volume model	$B = 30.3555 + 0.0885565 \cdot V$ cone	0.07	11.17	8.65
Parabolic volume model	$B = 30.3555 + 0.0590377 \cdot V$ paraboloid	0.07	11.17	8.65
Hemispheric volume model	$B = 30.3535 + 0.048627 \cdot V$ hemisphere	0.06	11.23	8.65

B: dry biomass (kg); R^2: coefficient of determination; sd: standard deviation; MAE: mean absolute error

The conical and parabolic volume models present the same very low coefficient of determination. The parabolic model is described below (Table 73).

Table 73. Significance of explicative variables for biomass prediction of *Phoenix dactilifera*

Dependent variable: B				
Independent varable: V paraboloid				
Parameter	Estimate	Standard error	T statistic	P-Value
Constant	30.3555	4.63231	6.55299	0.0000
V paraboloid	0.0590377	0.0421119	1.40192	0.1728

B: dry biomass (kg)

An analysis of variance was done to compare both species of palm trees: *Phoenix dactilifera* and *Phoenix canariensis*. The results are presented in Figure 23.

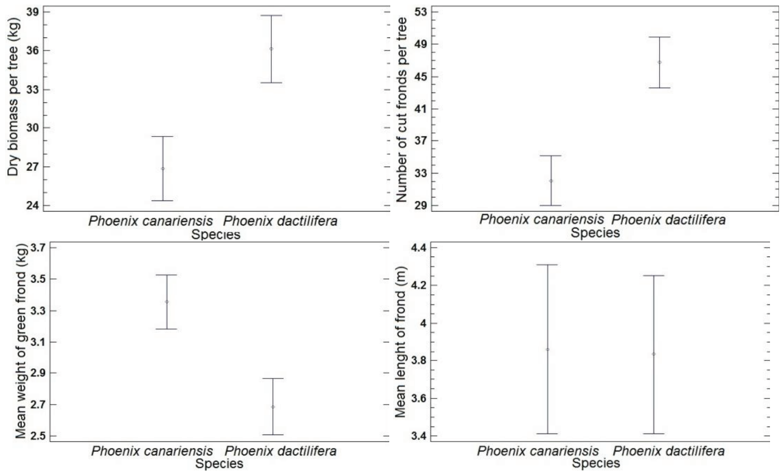


Figure 23. LSD intervals for the comparison of the residual biomass for *Phoenix dactilifera* and *Phoenix canariensis*: dry biomass per tree, number, mean weight and length of pruned leaves

Figure 23 demonstrates that the *Phoenix canariesis* has heavier leaves than the *Phoenix dactilifera*. While the *Phoenix dactilifera* is characterized with a higher number of cut fronds per palm.

The results demonstrate lack of interdependence between lonely examined parameters and quantity of yielded residual biomass. This is the consequence of the characteristics of palms. Palms being monocots have a different anatomy and form than other studied trees. The diameter at breast height does not increase with age. Therefore it is logical that no dependence can be seen between diameter at breast height and quantity of biomass. Moreover, the total tree height is never reduced during pruning operations as in this part, the youngest leaves are formed and also the terminal bud is located. Pruning this part would result in the death of the palm. Finally, the crown diameter practically does not decrease after the palm is pruned. This is caused by the characteristic form that palm leaves form in the canopy. The fronds of *Phoenix canariesis* are longer (mean 3.86 m) and heavier (mean 3.35 kg) comparing to *Phoenix dactilifera*. On the other hand, the study showed that the quantity of cut fronds per palm is higher in case of *Phoenix dactilifera* (mean 46.75 fronds).

When all prediction models for *Platanus hispanica, Morus alba*, *Sophora japonica*, *Phoenix canariensis* and *Phoenix dactilifera* were analysed, we reached the following conclusions. The results of this research cannot be compared directly to other studies as no data seem to be available or published on allometric equations for biomass prediction from pruning urban trees. However, some aspects may be similar to research conducted on all aboveground biomass estimates for forest and landscape trees. The results of this thesis are similar to other reports in that the dbh alone is a good predictor of biomass in the whole plant (McHale et al., 2009, Pillsbury et al., 1998, Eamus et al., 2000, Jenkins et al., 2004) and that its advantage over other parameters is associated with the accuracy, practicability and cost of measurement (Kuyah et al., 2012). In this study dbh when used as the only explanatory variable provided satisfactory estimation of biomass in case of *Platanus hispanica* and *Sophora japonica* yielding coefficients of determination R^2=0.80 and R^2=0.57, respectively. Similar to Ketterings et al., 2002, it was found, that including the total tree height in the prediction models improves the R^2 in contrast to the findings of Kuyah et al., (2012). When considering the crown diameter, good results were obtained for *Morus alba* street location (R^2=0.87), *Morus alba* park location (R^2=0.59) and *Platanus hispanica* (R^2=0.64). Even better results were observed, when including the crown volume in prediction models for *Morus alba* street location (R^2=0.90), *Morus alba* park location (R^2=0.59) and *Platanus hispanica* (R^2=0.78). Nevertheless, Kuyah et al., (2012) observe, that crown parameters are expected to increase the R^2 of prediction models but difficulties associated with measuring tree crown and its highly heterogeneous geometry are the reason of not including this parameter in equations. In contrast to other studies on all aboveground biomass from trees, a combination of all explanatory variables has been tested and led to improved results: *Morus alba* street location R^2=0.96, *Morus alba* park location R^2=0.88, *Platanus hispanica* R^2=0.93, *Sophora japonica* R^2=0.76, *Phoenix canariensis* R^2=0.88, *Phoenix dactilifera* R^2=0.67, respectively. Although very height coefficients were obtained, in many cases it may be complicated, costly and time consuming to measure these parameters. Moreover, the complexity of these models is a disadvantage over simple regression equations with only one variable. Information from other studies that calculated leaf-biomass from open grown urban trees based on equations derived from dbh and crown parameters indicated that estimates based on crown width gave better results than from diameter at breast height. Nevertheless, both may tend to overestimate biomass in cases as pruning (Gacka-Grzesikiewicz, 1980, Nowak, 1996). A study by Dobbs et al., (2011) estimated crown biomass by equations developed on data from randomized branch sampling. The findings of this work included, that some of the equations may overestimate biomass in smaller trees due to different growth rates of diameter and height.In addition, some studies have been carried out to calculate pruned biomass in agricultural trees. The study performed by Fernandez-Gonzalez (2010) calculated prediction models from different combinations of dendrometric variables, such as breast height diameter, crown diameter, total height or crown height. The R^2 obtained were between 0.6-0.95, therefore these equations gave similar level of coefficients of determination to those obtained in our study for predicting residual biomass for urban trees.

5.2. APPLICATION OF TLS FOR CALCULATION OF DENDROMETRIC PARAMETERS

5.2.1. Comparison of TLS data with direct measurements

Table 74 contains the values of tree height (h), distance from soil to the crown (hc), crown height (ch) and crown diameter (dc) of 30 specimens of *Platanus hispanica* obtained from terrestrial laser scanning and from manual *in situ* measurements.

Table 74. Tree parameters extracted from TLS point clouds and classical observations

Tree number	h (m)	h TLS (m)	hc (m)	hc TLS (m)	ch (m)	ch TLS (m)	dc (m)	dc TLS(m)
1	10.20	9.77	3.10	3.38	7.10	6.39	6.45	6.38
2	9.20	9.12	2.50	3.16	6.70	5.96	5.00	4.95
3	12.50	12.23	4.20	4.25	8.30	7.97	8.85	10.68
4	10.50	10.09	3.40	3.38	7.10	6.70	6.55	6.48
5	12.70	11.75	3.90	3.71	8.80	8.04	8.25	10.72
6	12.30	12.87	3.70	3.89	8.60	8.98	8.10	8.05
7	11.20	11.46	3.40	4.17	7.80	7.29	8.30	8.73
8	12.20	11.66	4.10	4.28	8.10	7.37	7.40	7.77
9	11.80	11.10	4.30	4.30	7.50	6.79	8.10	8.72
10	12.00	12.08	3.90	3.56	8.10	8.52	8.65	9.23
11	6.40	9.10	2.30	2.91	4.10	6.19	5.60	5.92
12	8.20	11.36	3.20	4.03	5.00	7.32	8.30	8.00
13	11.00	10.61	3.70	3.59	7.30	7.01	7.85	8.16
14	11.50	11.24	4.60	4.31	6.90	6.93	8.31	8.66
15	9.40	9.69	3.90	3.30	5.50	6.38	5.62	5.94
16	9.20	9.41	4.10	3.57	5.10	5.83	5.41	5.76
17	10.30	10.31	4.20	3.70	6.10	6.61	6.30	7.10
18	10.40	10.77	3.90	3.93	6.50	6.83	6.75	6.97
19	12.40	12.19	3.80	3.90	8.60	8.29	9.50	9.95
20	8.50	8.94	2.20	2.24	6.30	6.69	4.10	4.27
21	13.30	12.58	2.60	4.09	10.70	8.48	10.86	12.12
22	9.20	9.28	3.10	3.72	6.10	5.56	5.60	5.10
23	12.60	12.72	3.90	3.82	8.70	8.90	9.74	10.50
24	13.20	12.70	3.60	4.43	9.60	8.27	10.35	10.77
25	9.90	12.34	3.40	3.78	6.50	8.56	9.42	10.08
26	12.00	11.61	3.70	4.13	8.30	7.48	7.89	8.47
27	11.80	10.22	4.60	3.98	7.20	6.23	9.37	8.22
28	13.00	12.89	4.00	3.99	9.00	8.90	10.97	11.19
29	11.80	12.39	4.20	4.74	7.60	7.65	9.35	9.28
30	11.30	11.55	3.80	3.94	7.50	7.60	10.35	11.58
Maximum	13.30	12.89	4.60	4.74	10.70	8.97	10.97	12.12
Minimum	6.40	8.94	2.20	2.24	4.10	5.56	4.10	4.27
Mean	11.00	11.13	3.64	3.81	7.35	7.32	7.90	8.32
Standard deviation	1.67	1.27	0.62	0.49	1.44	0.99	1.83	2.12

To compare dendrometric parameters obtained with both methodologies an analysis of variance was performed.

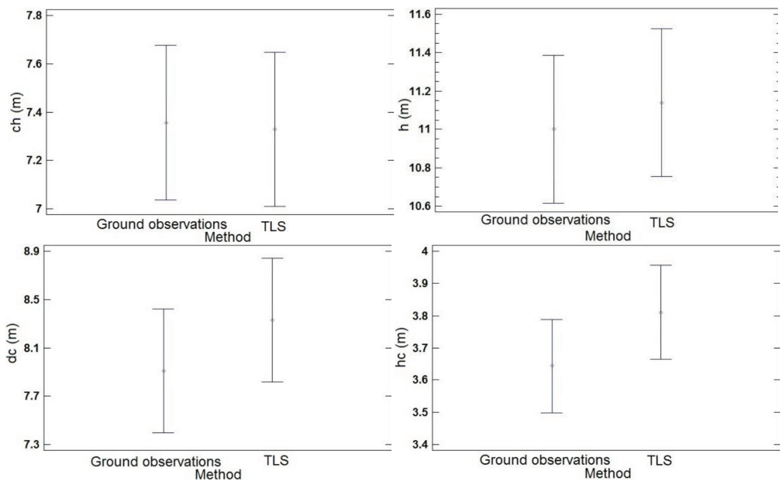


Figure 24. Intervals of statistical comparison of the dendrometric measurements carried out manually and by means of TLS for 30 sample trees: ch: crown height (m); h: total tree height (m); dc: crown diameter (m); hc: distance from soil to the crown (m);

The results indicate that there are no significant differences (P-values<0.05) within the analyzed parameters obtained with 2 different methods, although the average of total tree heights obtained in field trials is somewhat lower than the obtained by TLS. This may be caused by improper registration of the peak of the canopies due to the proximity of the scanner to sample trees. This may also indicate, that trees tend to be underestimated while ground-based measurements. The average crown diameter calculated manually in field trials is also somewhat lower than the extracted from TLS point clouds, however they do not present statistical differences in the ANOVA. One reason of underestimation may be attributed to the existence of obstructing elements in the form of neighbour trees. In many cases the border between branches of neighbour tree crowns is hard to define from ground level. On the other hand, it is considered, that values obtained with programming are very precise. These results point that classical methods give acceptable values. 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). In case of distance from soil to the crown the difference of the means may be explained by the criteria assigned for the selection of the canopy base. An inter-comparison by means of regression models of structural parameters was made for data obtained with both methodologies (Figure 25). Coefficients of determination and mean absolute errors were determined.

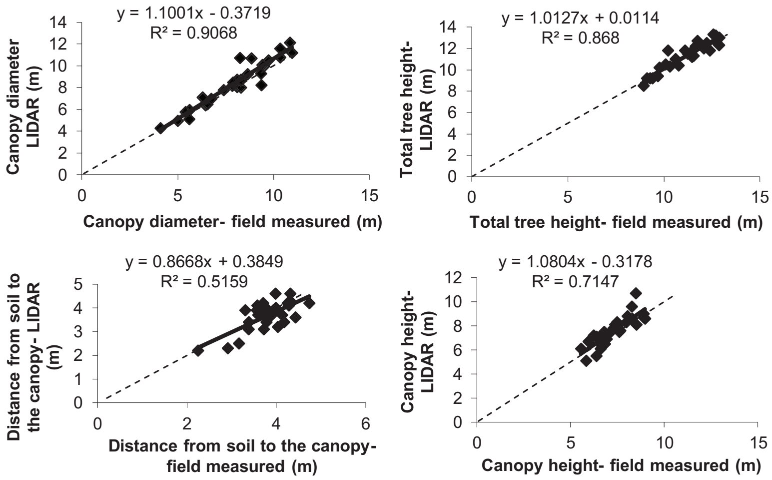


Figure 25. Inter-comparison of parameters obtained from TLS point clouds and ground observations for 30 sample trees: canopy diameter (m); total tree height (m); distance from soil to the crown (m); canopy height (m)

Figure 25 shows that the models highly explain the relation (R^2=0.90) between crown diameters and a good relationship between total tree heights (R^2=0.86). On the other hand, the models which relate the distance from soil and the crown results show the lowest levels of R^2 within both methodologies. This may be explained by the criteria assigned for the selection of the canopy base. In case of manual measurement as a 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 (A [No.] T.xyz) and (A [No.] .xyz) files containing 3D scans of tree trunks and total tree heights.

The analysis of two different methods of tree data collection in this study revealed some potential errors that should be considered for future crown structure studies. TLS data collection of crown physical dimensions on an individual tree level showed advantages and disadvantages of the technology. The tripod-mounted TLS scans may capture crown height ineffectively, because a part-point registration along the Z-axis (height) may occur in case of inaccurate TLS distance from target tree. This may lead to misestimating of total tree height. However, laser pulse reflection registers along the Y-axis (width) are very precise if not interfered with obstructing elements. The advantage of TLS approach is that it is quicker than time-consuming ground methods that run risk of potential observer error. In this study the ground-based and TLS-based approach was inter-compared. Crown diameter obtained by TLS strongly correlated with data obtained from ground observations with a coefficient of determination of R^2=0.90. On the other hand, the inter-comparison of both approaches for variable distance from soil to the crown indicated the lowest coefficient of determination of all analyzed physical tree dimensions (R^2=0.51). This may be caused by the difference in estimating the base of the canopy variable in both methodologies. As for canopy height (R^2=0.71), this variable is dependent from other two parameters namely total tree height and distance from soil to the crown. Any error committed when calculating the previously mentioned, influences the accuracy of this variable.

5.2.2. **Comparison of TLS data with crown volume**

Table 75 contains values of the crown volumes of 30 specimens of *Platanus hispanica* obtained from TLS data applying the four mentioned methods (global CH, CH layers, sections, voxel) and from field measurements applying solids of revolution (paraboloid, hemisphere, cone). As can be observed, the greatest values of volume calculated from TLS data were obtained using the global CH method, followed by the methods by sections and CH layers, which are very similar. The lowest volumes were obtained using the method based on voxels. This result can be explained by the fact, that some holes are not detected within the crown due to either the occultation by the external leaves - branches or their real absence (Figure 26). The volumes calculated using solids of revolution from classical dendrometry were lower than those obtained from TLS data.

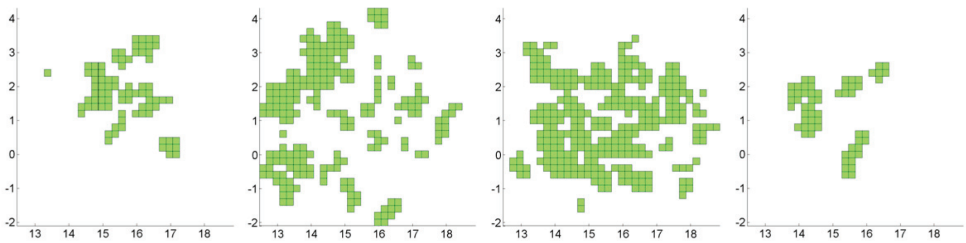


Figure 26. Position of the voxels in four horizontal sections at 3, 5, 7 and 9m height of tree

A large dispersion can be observed in the population (standard deviation), because the sampled trees had different degrees of development (growth). The young trees show a vertical development and the mature trees (most of the sampled trees) are characterized by a horizontal expansion while their geometric shape is close to a paraboloid. The values of skewness and kurtosis were close to 0 indicating a good approximation to the normal distribution. This fact is very important given that different analyzes to compare the volumes derived from classical dendrometry and TLS data are allowed.

Table 75. Volumes (m^3) obtained for each of the 7 methods of calculation and their basic statistics

	TLS				Field measured		
Tree number	Global CH	Ch layers	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
Standard deviation	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
Shapiro-Wilks test (P-value)	0.276	0.238	0.225	0.225	0.173	0.193	0.173

To compare the volume calculated by means of the different methods, the analysis of variance was carried out. The LSD intervals at 95 % are shown in the Figure 27. This comparison has been carried out in three phases:

- Comparison between dendrometric volumes,
- Comparison of the volumes obtained from the TLS,
- Comparison between dendrometric volumes and volumes calculated from TLS.

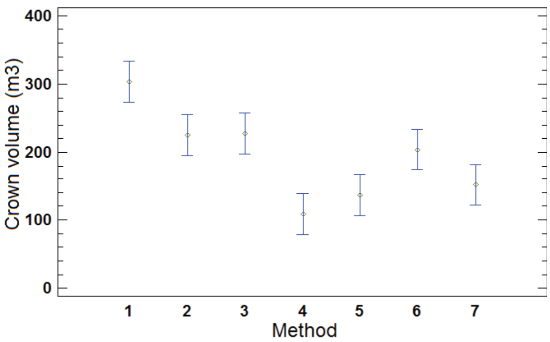


Figure 27. LSD intervals for calculation methods: 1-global CH; 2-CH layers; 3-sections; 4- voxel; 5- paraboloid; 6-hemisphere; 7-cone

As can be observed in the Table 76, the comparison between each two methods by linear regression models show high coefficients of determination. The analysis between methods applied to TLS data show 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 76. Equations and R^2 coefficient adjustment of the different calculation methods

Equation / R^2	Paraboloid	Hemisphere	global CH	CH Layers	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 Layers	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	

a) Comparison between dendrometric volumes

Figure 27 shows significant differences between the paraboloid and hemisphere. Figure 28 compares these volumes obtained using regression models. The dashed line represents the bisector line where both volumes are similar. It can be observed, that the crown volumes obtained from the paraboloid model are greater than those obtained from the hemispheric model, presenting points above the dashed line. However, some exceptions were found that could be explained considering some factors such as pruning or distance to buildings that could affect the growth and shape of the trees. Also, it can be observed that the points are distributed uniformly along the trend line, which shows the absence of anomalous points. In addition, there was proportionality among the volumes calculated using both geometric shapes according to equation (7). The results obtained from manual measurement at field of 30 specimens show that the average of the proportionality factor was 0.72 (Table 77) with a standard deviation of 0.13.

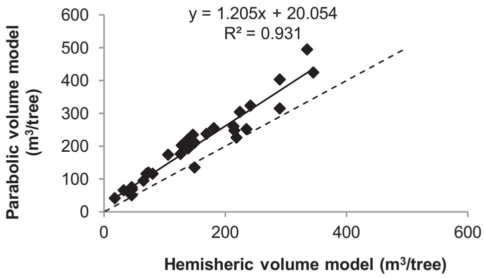


Figure 28. Paraboloid versus hemisphere volume of the crown (m^3) (30 sample trees)

Table 77. Statistical values of proportionality factor between the paraboloid crown model and hemisphere crown model

	dc/hc	K =2/3 * (dc/hc)
Mean	1.08	0.72
Standard deviation	0.20	0.13

dc: crown diameter (m); hc: distance from soil to the crown (m)

b) Comparison of the volumes obtained from the TLS

The global CH method provided the highest values of volumes (Figure 27). This is consistent with the nature of the method, which creates a solid surrounded by triangles whose vertices are the most exterior points of the point cloud data registered by the TLS. This volume includes all internal holes of the crown and external spaces between branches, generating an overestimation of the apparent volume.

The three-dimensional modelling by voxels gave the lowest values of volumes, approximately one third lower than the volumes obtained by the previous method. This can be explained by the fact that the rasterization is done according to 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, it is the method that performs best the actual shape of the crown with its branches and leaves. Nevertheless, it 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. (This limitation can be overcome using a greater scan resolution and number of base stations). For the mentioned reasons, these volume values are lower than actual volume, but can be used to calculate dendrometric variables, such as crown diameter and height or to be related with residual biomass.

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

The CH by layers and volume calculation by sections show very similar results and 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 convex hull. As can be observed in Table 76, the comparison between volumes generated using the CH by layers and section method 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 methods global CH and CH by layers (R^2 = 0.99). Good results were also obtained among volumes obtained using the CH layers and rasterization in voxel method (R^2 = 0.94).

c) Comparison between dendrometric volumes and volumes calculated from TLS

A comparative analysis was performed for finding relationships between the volumes obtained applying classical dendrometry (paraboloid) and TLS data processing (Figure 29 and Table 76). Values of R^2 were between 0.78 and 0.89. All volumes obtained from TLS data were higher than those obtained from the paraboloid model except for the volumes obtained from voxel quantification. It is also observed that the volumes of smaller trees were usually located near the diagonal. Greater differences were found for mature trees, what could be explained by the larger irregularities in their crowns. The relation between the paraboloid and volume calculation by sections gave the highest coefficient of determination (R^2) what means that this processing method could be used to estimate some dendrometric variables used to calculate the paraboloid volume such as crown diameter and height. It is important to note that the findings of this method are also very close to the CH layers method. The volumes obtained by quantification of voxels gave the lowest values, and the equations had the smallest R^2.

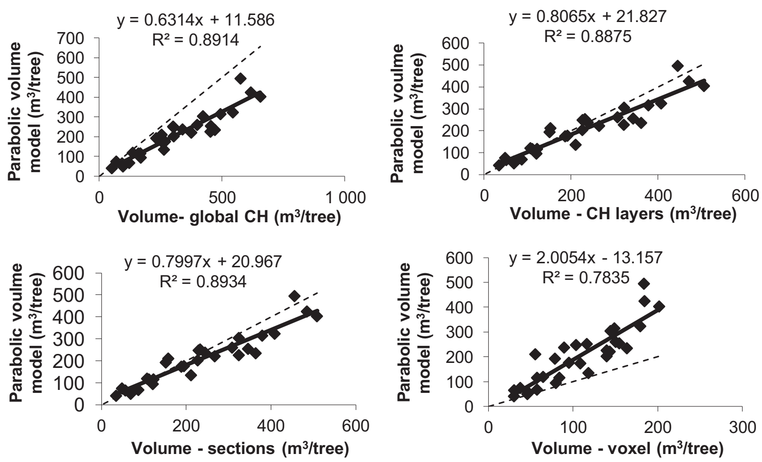


Figure 29. From left to right and up to down: Relationships between volume of the paraboloid and the volumes obtained from TLS data for 30 sample trees: global CH; CH layers; sections; voxel

An important variable to evaluate each method is the number of operations required and the processing time. Figure 30 shows a comparative analysis of this parameter for the 4 methods used to process the point clouds 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 small trees (minor number of points). However they were very significant for larger crowns.

The method based on voxel model, generated the highest variation of processing time, being almost three times the one required for the volume computation using the section method in big trees. This increase was not linear. The global Convex Hall and the Convex Hull by layers were the fastest methods, and they showed the lowest increase in the processing time for larger crown size. These variations were linear with a low gradient.

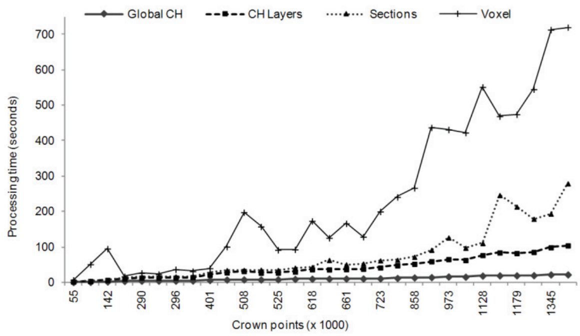


Figure 30. Processing time for each tree crown and the 4 methods applied to laser data

The relative peaks observed in the section method and voxel rasterization are explained by the distribution of points within a crown.

Concerning the voxel method, it is important to mention that a voxel with a high concentration of points and a voxel with few points are processed with only one operation. This means, that depending on point distribution, a crown with bigger number of points can have less or the same quantity of voxels and be processed in less or equal time than a crown with less TLS points. In general, the tendency is that the processing time increases with the number of points but occasionally can be found crowns with peak points.

In the case of the section method the external points are selected for crown volume calculation. Therefore, the distribution of points inside and in the external layer influences the processing time. It may occur that a crown with high number of points inside and few external points was processed faster than other crown with few TLS data but a lot of external points.

5.2.3. **Prediction of residual biomass from TLS data**

Pruned biomass was correlated with 4 methods of crown volume calculations extracted from TLS point clouds (Figure 31).

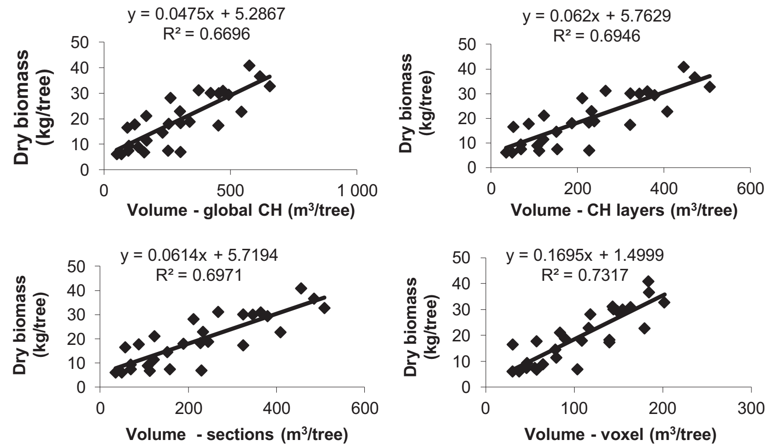


Figure 31. From left to right and up to down: Relationship between 4 methods of TLS volume calculation and yielded biomass from 28 sample trees: global CH; CH layers; sections, voxels

The results are similar for all analysed models. The best coefficient (R^2=0.73) is observed between biomass and volume processed from voxels. This is explained by the accuary of voxel method and best adjustment to crown architecture. However, minor differences of coefficients in all analysed models indicate that less time-consuming processing methods give satisfying results (run risk of low error). Biomass obtained from pruning was also correlated with goemetrical crown volumes (Figure 32).

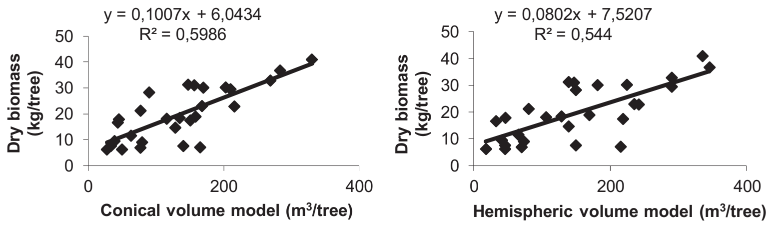


Figure 32. Relationship between 2 methods of volume calculation (cone, hemisphere) and yielded biomass from 28 sample trees

The conical and parabolic volume models are proportional and indicate a coefficient of R^2=0.59. The result is lower than the relation obtained with volumes extracted from point clouds. This explains higher precision of TLS over ground-level measurement.

The inter-comparison of pruned biomass with volumes extracted from point clouds revealed the highest accuracy of the voxel method and its adjustment to crown architecture (R^2=0.73). However minor differences of coefficients in all analysed models indicated, that less time-consuming processing methods give similar results and run risk of low error. The results obtained with geometrical volume models presented lower coefficients of 0.59 and 0.54, respectively. Results obtained with both methodologies demonstarte relationship between examined parameters and possibility of predicting biomass from volume.

The results concerning residual biomass prediction from pruning urban trees obtained from processing point clouds cannot be compared directly to other studies as no published data have been found on the topic. Nevertheless, studies exist on LIDAR application to estimate crown structure, stem volume.

5.3. ENERGY CHARACTERIZATION OF THE RESIDUES

5.3.1. Elemental composition

In Table 78 are presented the values of elemental composition and gross calorific value of the studied biomass dried in stove and wet up to 10%.

Table 78. Analysis of elemental composition of examined biomass

Variable	Species	Drying process	Average	Standard deviation	Standard skewness	Standard kurtosis	Maximum	Minimum
GCV (kJ/kg)	*Morus alba*	W10	17127.62	157.02	-1.04	0.04	17301.25	16834.74
	Morus alba	Dry	18192.86	554.08	0.37	-0.60	19099.12	17396.23
	Phoenix canariensis	W10	14655.71	742.24	0.74	-0.81	15722.63	14000.91
	Phoenix canariensis	Dry	16029.23	377.56	-1.57	1.67	16434.33	15321.38
	Phoenix dactilifera	W10	15134.07	1193.27	-0.81	-0.80	16286.63	13452.39
	Phoenix dactilifera	Dry	16975.19	444.84	1.00	0.86	17752.29	16466.55
	Platanus hispanica	W10	17513.76	356.56	-0.01	-1.10	17972.79	17084.94
	Platanus hispanica	Dry	18952.47	556.93	-0.08	-0.84	19707.47	18195.79
	Sophora japonica	W10	17970.48	198.40	1.16	-0.03	18317.13	17746.43
	Sophora japonica	Dry	19615.67	100.75	-1.20	1.66	19754.33	19418.78
% C	*Morus alba*	W10	44.54	0.38	-0.15	-0.88	45.0	44.0
	Morus alba	Dry	48.22	0.67	-0.11	-0.37	49.3	47.2
	Phoenix canariensis	W10	39.11	1.45	0.52	-0.90	40.9	37.5
	Phoenix canariensis	Dry	42.36	1.71	0.65	-0.25	45.0	40.3
	Phoenix dactilifera	W10	39.43	1.96	-0.69	-0.82	41.3	36.7
	Phoenix dactilifera	Dry	44.36	1.07	0.14	-0.78	45.7	43.0
	Platanus hispanica	W10	44.1	0.58	0.41	-0.47	45.0	43.3
	Platanus hispanica	Dry	48.48	0.64	0.41	-1.22	49.3	47.8
	Sophora japonica	W10	45.66	0.53	-0.10	1.15	46.6	44.7
	Sophora japonica	Dry	49.15	0.63	-0.23	-0.16	50.1	48.1
% H	*Morus alba*	W10	6.36	0.07	0.48	-0.94	6.45	6.26
	Morus alba	Dry	5.92	0.03	-0.28	-0.73	5.97	5.87
	Phoenix canariensis	W10	5.65	0.26	-0.58	-0.88	5.9	5.3
	Phoenix canariensis	Dry	5.50	0.47	-0.55	0.08	6.09	4.75
	Phoenix dactilifera	W10	5.99	0.27	-0.58	-0.90	6.26	5.62
	Phoenix dactilifera	Dry	5.78	0.23	-0.64	-0.98	6.0	5.48
	Platanus hispanica	W10	5.83	0.08	0.89	0.72	5.99	5.73
	Platanus hispanica	Dry	5.77	0.00	-0.51	-0.27	5.87	5.69
	Sophora japonica	W10	6.54	0.06	0.28	0.39	6.67	6.44
	Sophora japonica	Dry	6.17	0.10	-1.37	1.35	6.3	5.97
%N	*Morus alba*	W10	0.60	0.14	0.64	-0.88	0.83	0.45
	Morus alba	Dry	0.86	0.13	-1.04	-0.60	1.01	0.62
	Phoenix canariensis	W10	0.33	0.02	0.18	-1.19	0.36	0.31
	Phoenix canariensis	Dry	0.41	0.01	0.85	-0.19	0.44	0.40
	Phoenix dactilifera	W10	0.49	0.02	0.03	-0.40	0.53	0.45
	Phoenix dactilifera	Dry	0.61	0.03	1.02	-0.68	0.66	0.58
	Platanus hispanica	W10	0.67	0.12	0.15	-1.08	0.85	0.51
	Platanus hispanica	Dry	0.78	0.13	-0.16	-1.02	0.94	0.61
	Sophora japonica	W10	0.90	0.21	1.69	0.78	1.34	0.72
	Sophora japonica	Dry	1.16	0.17	0.76	-0.64	1.42	0.98
% S	*Morus alba*	W10	0.04	0.00	-1.67	1.54	0.05	0.04
	Morus alba	Dry	0.05	0.00	0.42	-0.57	0.05	0.04
	Phoenix canariensis	W10	0.44	0.07	0.02	-0.47	0.54	0.34
	Phoenix canariensis	Dry	0.48	0.06	0.87	-0.50	0.59	0.42
	Phoenix dactilifera	W10	0.45	0.15	1.40	0.56	0.32	0.73
	Phoenix dactilifera	Dry	0.43	0.03	0.87	-0.86	0.48	0.40
	Platanus hispanica	W10	0.05	0.00	-0.82	-0.74	0.05	0.04
	Platanus hispanica	Dry	0.05	0.00	0.63	-0.11	0.06	0.04
	Sophora japonica	W10	0.05	0.00	-1.92	1.85	0.05	0.03
	Sophora japonica	Dry	0.05	0.00	-0.51	-0.45	0.05	0.04
% bark	*Morus alba*		9.49	3.83	1.20	-0.17	17.82	3.13
	Platanus hispanica		13.05	4.80	1.74	0.92	25.43	6.57
	Sophora japonica		5.29	3.53	1.49	-0.18	13.46	0.14

W10: sample up to 10% moisture content in wet basis; GCV: gross calorific value (kJ/kg); C: carbon (%); H: hydrogen (%); N: nitrogen (%); S: sulfur (%)

As it can be observed, all variables show standard kurtosis and standard skewness between -2 and + 2. This fact means that all of them follow a normal distribution, which is essential for the analysis. The average GCV of analyzed species range between 14-20 MJ/kg depending on moisture content what gives similar results to those published by Gillon et al., (1997) on residuals from landscape maintenance of broad-leaved species (18.80-21.10 MJ/kg) and by Yin (2011) for biomass (14-23 MJ/kg). These results are also approximated to those found by FAO (2004) on net calorific value of road side green 14,1MJ/kg and Castells (2005) for park residuals and wood slightly above 4000 kcal/kg. The GCV found in this thesis are similar to those for agricultural residuals (15-17 MJ/kg) and to woody materials (18-19 MJ/kg) (Vargas Moreno, 2012).

To compare the GCV of different species, the analysis of variance was carried out. The LSD intervals at 95 % are shown in the Figure 33. It is observed, that the GCV is significantly different among the studied species.

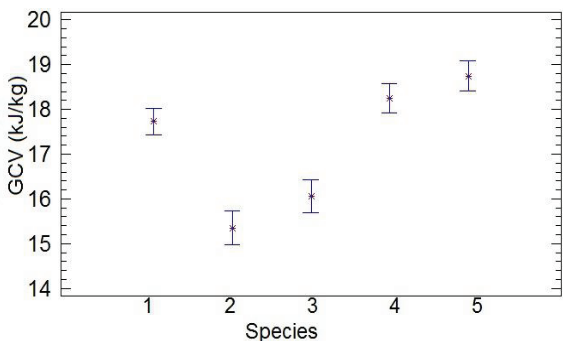


Figure 33. LSD intervals for GCV of species: 1-*Morus alba*; 2-*Phoenix canariensis*; 3-*Phoenix dactilifera*; 4-*Platanus hispanica*; 5- *Sophora japonica*

The dependence of the studied variables is shown in the Table 79. It can be noted that moisture content, %C, and %H have a high influence in the Gross Calorific Value (GCV) when are considered lonely what is also observed in other studies (Callejon et al, 2011, Telmo et al., 2010). Nevertheless, it is important to point that the high %H is related with the moisture content of the material, given that the water has as formula H_2O. The water content in the pores of the biomass modifies the weight of the material and the ratio of the other elements in the sample composition.

In the Table 78 can be seen that the stove-dried samples present higher mean concentration of carbon and calorific value while the %H generally decreases in dried environment. This is explained by the additional energy that must be used for H_2O evaporation for samples with moisture contents above 0%. The palms are observed to have the lowest calorific values and %C within the studied species. On the other hand they present 10 times higher concentration of sulphur then other sample trees. Sulphur can be dependent from high concentration in soil and air environment. The results also indicate that

Sophora japonica is the species with highest values within most studied parameters (excluding %S). The concentration of C and H in the studied biomass was approximately 40-50% and 5.5-6.5% what is found in the range for published data (C=42-71%, H= 3-11%) (Vassilev et al., 2010). The N and S concentration in the examined residuals estimated at the level of 0.3-1.1% and 0.04-0.48% are low comparing to those found in literature for biomass (N=0.1-12%, S=0.01-2.3%) (Vassilev et al., 2010, Khan et al., 2009). This result is an advantage, as high concentration of N and S produces negative impact on environmental due to the emission of nitrogen oxides, sulfur dioxide and sulfur trioxide during combustion (Khan et al., 2009; Elmo et al., 2010).

Table 79. Multidimensional analysis of studied elemental composition

Morus alba	% Moisture content	% C	% H	% N	% S	GCV (kJ/kg)
% Moisture content		-0.9672*	0.9789*	-0.7399*	-0.4512	-0.7750*
% C	-0.9672*		-0.9248*	0.8505*	0.4747	0.6495*
% H	0.9789*	-0.9248*		-0.6855*	-0.4823	-0.8530*
% N	-0.7399*	0.8505*	-0.6855*		0.6278*	0.4730
% S	-0.4512	0.4747	-0.4823	0.6278*		0.5724
G CV(kJ/kg)	-0.7750*	0.6495*	-0.8530*	0.4730	0.5724	
Phoenix canariensis	% Moisture content	% C	% H	% N	% S	GCV(kJ/kg)
% Moisture content		-0.7118*	0.1985	-0.9013*	-0.3062	-0.7900*
% C	-0.7118*		0.3719	0.5653	-0.0111	0.8093*
% H	0.1985	0.3719		-0.0612	-0.2266	0.0258
% N	-0.9013*	0.5653	-0.0612		0.4111	0.5777
% S	-0.3062	-0.0111	-0.2266	0.4111		-0.1626
GCV(kJ/kg)	-0.7900*	0.8093*	0.0258	0.5777	-0.1626	
Phoenix dactilifera	% Moisture content	% C	% H	% N	% S	GCV(kJ/kg)
% Moisture content		-0.8800*	-0.4112	-0.8867*	0.0044	-0.7576*
% C	-0.8800*		0.7507*	0.8388*	-0.1829	0.9346*
% H	-0.4112	0.7507*		0.5483	-0.0973	0.7162*
% N	-0.8867*	0.8388*	0.5483		0.3413	0.6669*
% S	0.0044	-0.1829	-0.0973	0.3413		-0.4006
GCV(kJ/kg)	-0.7576*	0.9346*	0.7162*	0.6669*	-0.4006	
Platanus hispanica	% Moisture content	% C	% H	% N	% S	GCV(kJ/kg)
% Moisture content		-0.9619*	0.4550	-0.3955	-0.3119	-0.8210*
% C	-0.9619*		-0.2451	0.5867*	0.3198	-0.9221*
% H	0.4550	-0.2451		0.3346	-0.3913	-0.0822
% N	-0.3955	0.5867*	0.3346		-0.0111	0.7832*
% S	-0.3119	0.3198	-0.3913	-0.0111		0.2210
GCV(kJ/kg)	-0.8210*	0.9221*	-0.0822	0.7832*	0.2210	
Sophora japonica	% Moisture content	% C	% H	% N	% S	GCV(kJ/kg)
% Moisture content		-0.9823*	0.9714*	-0.6481	-0.5947	-0.9825*
% C	-0.9823*		-0.9427*	0.7122*	0.5295	0.9834*
% H	0.9714*	-0.9427*		-0.4907	-0.5908	-0.9327*
% N	-0.6481	0.7122*	-0.4907		0.0520	0.7522*
% S	-0.5947	0.5295	-0.5908	0.0520		0.4682
GCV(kJ/kg)	-0.9825*	0.9834*	-0.9327*	0.7522*	0.4682	

* pares of variables with P-values lover then 0.05; GCV: gross calorific value (kJ/kg); C: carbon (%); H: hydrogen (%); N: nitrogen (%); S: sulphur (%)

For indirect GCV calculation, prediction models from ratios of C, H, N, and S were developed. These models have high importance in the industry because the GCV of material is used in boilers and is usually unknown due to the influences of moisture content as demonstrated (Table 78 and 79). The GCV determination with adiabatic calorimeter AC-500 takes 20 min/sample, and moisture content measurement takes 24 h using the norm UNE. According to experience with LECO CHN Truspec analyzer, the time of the elemental analysis is 5 min/sample. Therefore, the indirect measurement using regression equation from the ratios C, H, N and S lead to faster and consequently cheaper determinations (Table 80).

Table 80. Prediction models for indirect calculation of gross calorific value

Species	Function	R^2	sd	MAE
Morus alba	GCV = 3674.57 + 302.93·C	0.66	421.97	328.48
Phoenix canariensis	GCV = 1295.20 + 344.77·C	0.74	484.75	338.31
Phoenix dactilifera	GCV= -3333.57 + 571.06·C - 8194.02·N	0.93	349.65	253.92
Platanus hispanica	GCV= 4189.23 + 269.63 ·C + 2138.94·N	0.95	201.20	158.40
Sophora japonica	GCV= -2080.66 + 439.47·C	0.96	174.26	132.758

GCV: gross calorific value (kJ/kg); C: carbon (%); N: nitrogen (%)

All models present high R^2 and can be used to calculate the gross calorific value without the need of a calorimeter. This allows shortening the measurement process when necessary. The P-value in all explicative variables was lower than 0.05.

5.3.2. **Determination of moisture content**

Figures 34, 35, 36, 37 and 38 show the variation of moisture content during the evaluation of the drying process carried out in both open-air drying conditions. It is observed that the minimum moisture content in open-air was obtained between 25-40 days.

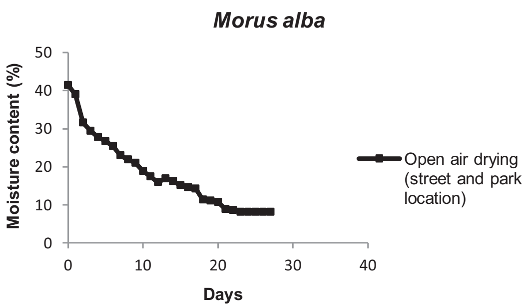


Figure 34. Drying curve for *Morus alba*

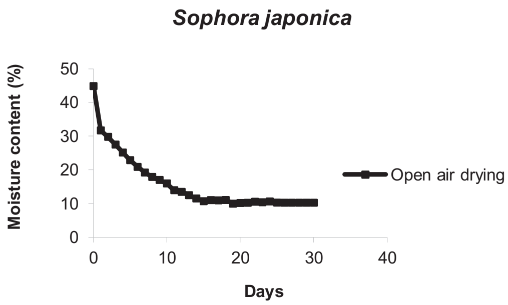


Figure 35. Drying curve for *Sophora japonica*

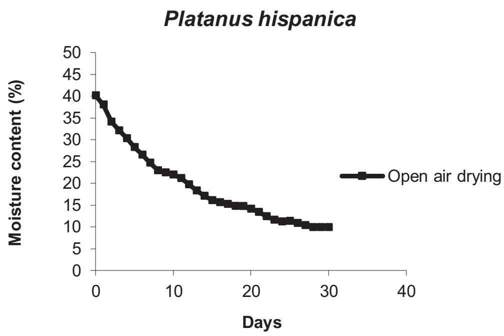


Figure 36. Drying curve for *Platanus hispanica*

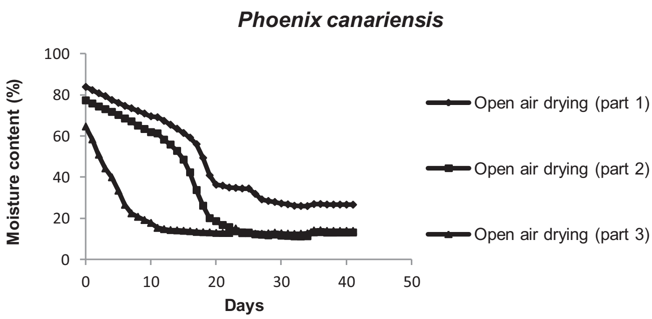


Figure 37. Drying curve for *Phoenix canariensis*

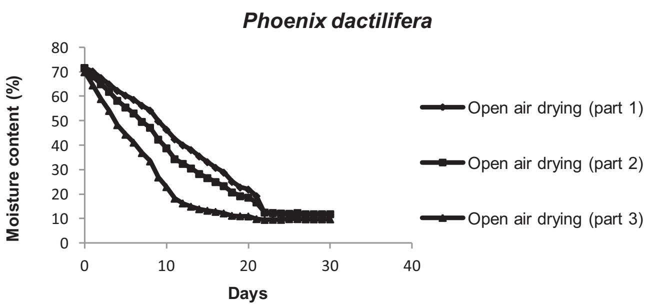


Figure 38. Drying curve for *Phoenix dactilifera*

5.3.3. **Determination of wood density**

In Table 81 can be observed that the species with highest mean density value is the *Sophora japonica.* According to published data *Morus alba* yields a medium-weight hardwood with density 670-850 kg/m^3 while *Platanus hispanica* 625 kg/m^3 (World Agroforestry Center, 2012). Wood density varies depending on growth conditions and part of the tree measured. The main stem is characterized with higher density than the branches what may explain the lower results obtained in this study.

Table 81. Density of analyzed species

Species	Mean (g/cm^3)	sd
Morus alba	0.60	0.04
Phoenix canariensis	0.65	0.14
Phoenix dactilifera	0.77	0.07
Platanus hispanica	0.50	0.14
Sophora japonica	0.86	0.19

sd: standard deviation

To compare the wood densities of different species, the analysis of variance was carried out. The LSD intervals at 95 % are shown in the Figure 39. The wood density is significantly different among the studied species.

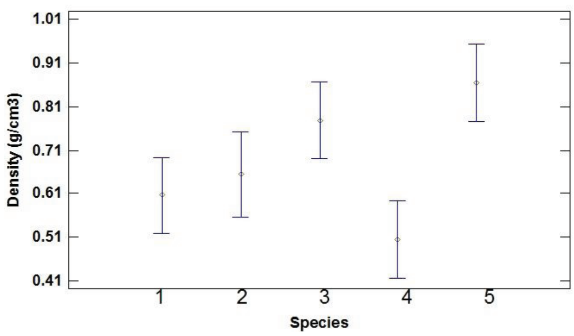


Figure 39. LSD intervals for wood density of species: 1-Morus alba; 2-Phoenix canariensis; 3-Phoenix dactilifera; 4- Platanus hispanica; 5- Sophora japonica

6. CONCLUSIONS

In this work has been found, that significant quantities of lignocellulosic residual biomass with possible energy and industrial end can be obtained from pruning urban forests.

Furthermore, indirect techniques for quantification of residual lignocellulosic biomass coming from mainetenance operations have been evaluated for the most important species of Mediterranean areas: *Morus Alba, Phoenix canariensis, Phoenix dactilifera, Platanus hispanica* and *Sophora japonica*. For this, three aproaches have been followed:

Firstly, prediction models based on allometric relationships between dendrometric parameters of the trees and quantity of yielded biomass have been developed. Secondly, a dendrometry characterization has been done. Its objetive was to allow calculating the actual volume of the branches from their base diameter and length. Thirdly, Terrestrial Laser Scanner (TLS) techniques have been evaluated. This approach led to substituting destructive sampling with every time more accurate, indirect methods.

This study has focused on biomass proceeding from pruning operations of urban forests. Numerous results of this thesis are a novel contribution to biomass research as no similar studies seem to be available or published.

6.1. ALLOMETRIC MODELS TO QUANTIFY RESIDUAL BIOMASS

Development of allometric equations applicable to urban forests is critical for non-destructive biomass estimation. It has been demonstrated that the residual biomass can be predicted from dendrometric variables in the studied species. The best functions have been obtained when several variables were combined in quadratics models. In case of *Platanus hispanica* the best explicative variables were diameter at breast height and crown diameter, or the apparent volume of tree crown obtained from conical model, which explained until 87% and 90 % of the population variability respectively. For *Morus alba*, significant differences have been found between trees located in streets and trees located in parks for all examined dendrometric parameters. The park location trees were bigger according to all examined variables. This influenced in the residual biomass quantity obtained from pruning, which was only formed by wood. Good results have been also found when correlating apparent crown volume with kilograms of yielded residual. *Morus alba, Platanus hispanica, Sophora japonica, Phoenix canariensis* and *Phoenix dactilifera* gave good models for predicting dried pruned biomass when the diameter at breast height, crown diameter, total height, and crown height were combined as explicative variables.

The obtained equations are a new tool for prediction of pruned residuals and can be used for biomass inventories in urban areas, planning the collection of these residues, and to establish policies for using these materials as feedstock.

Palm trees were those with greatest difficulty to be approximated to prediction models.

6.2. DENDROMETRIC CHARACTERIZATION OF BRANCHES

Two techniques have been evaluated to calculate the actual volume of the cut branches from their base diameter and length: using a form factor and volume functions. These, allow calculating the biomass when the branches cannot be weighted or they are in big bundles.

It has been verified that volume functions lead to better approximation to the actual volumes than the use of the form factor.

When the form factor is used to calculate the actual volume of a branch, the average must be used taking into account big dirpersion that exists in the obtained values. It has been found, that the form factor does not follow a tendency with variation of the base diameter and the length of the branch.

6.3. TERRESTRIAL LASER SCANNER (TLS) TECHNIQUES

Four procedures to calculate the canopy volume from modelling three-dimensional point clouds obtained by terrestrial laser scanner (TLS) have been developed and analyzed. After removing the noise error in the point clouds and separating the scan into individual tree files, 4 methods of volume calculation have been evaluated: *global convex hull* for the entire point cloud that forms the crown; *convex hull by layers* of 5cm height in the XY plane; triangulation by XY flat *sections*, and discretization of the point cloud in small elements of volume (*voxel*). Developed methods for apparent crown volume calculation allow obtaining high approximation to real crown shape.

It has been demonstrated that the volumes of smaller trees calculated from laser scanner have usually better proportionality to classical paraboloid volume than the bigger ones, due to their smaller irregularities. The processing method based on calculation by sections and the paraboloid method had the maximum coefficient of determination to calculate crown volume values. Considering the parameters of this geometric shape, this method could be also suitable to define 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 layers method.

The methods based on volume calculation by sections and Convex Hull by layers minimize the overestimation generated by the global Convex Hull method. The voxel method provided the smallest values of volumes and it was considered the best approximation to the real shape of the crown. This fact is caused by the partial detection of the structures in the inner part and complete detection in the outer part of canopy. This is not achieved with the other methods. For this reason, it is considered that the voxel method is the most accurate to estimate the biomass of the tree. However, the occultation of points inside of the crown by external leaves and branches can be a limitation for the use of this method to calculate actual volume. Other disadvantage is the higher computational time used to perform the calculations. In contrast, the global Convex Hull and the Convex Hull by layers are the fastest methods, and they show a lower increase in the processing time with bigger crown size.

All studied methods applied to TLS data have showed high correlation with the volumes obtained with the classical geometric models. These models have been related with variables used for plantation management, such as: amount of residual biomass from pruning. The methods developed in this study from TLS data may involve an important advance for the management of the studied trees.

Studies on TLS data demonstrate advantage over time-consuming direct tree measurement:

- Destructive sampling is substituted with accurate, indirect methods,
- Ground-level labour-intensive inventory practices are replaced with high data collection capacity remote sensing systems. TLS data can be used for precise characterization of vegetation architecture and yielded biomass at individual tree level. This approach eliminates risk of potential observer error,
- Introduced for applications in urban forests, TLS systems allow three-dimensional modelling and geometrical characterization of trees, making it easier to develop management systems based on precise information.

6.4. WOOD CHARACTERIZATION

Characterization of physical and chemical properties of pruned materials in order to evaluate their suitability for energy and industrial applications has been made. The evaluation of drying process has been studied. The *Morus alba*, *Platanus hispanica* and *Sophora japonica* species had around 45% moisture content in wet basis while the *Phoenix canariensis* and Phoenix dactilifera reached more than 70% of moisture content in wet basis. The highest density of all species presented *Sophora japonica* (0.86 g/cm^3).

C, H, N, S determination allows developing indirect methods to calculate the gross calorific value of the materials at different moisture content with high precision. The applicability of these indirect methods is justified by the long time taken in direct analysis by an adiabatic calorimeter.

On the other hand, the C, H, N, S determination allows also evaluating environmental benefits by the reduction of carbon dioxide emissions when these materials are used as a biofuel. Nevertheless, other benefits should be considered, such as conservation of landfill space, reduction of waste disposal cost and reduction of pressure on forests. From an environmental point of view, the increased recycling of recovered urban wood residual biomass can be seen as a positive evolution because it leads to incensement of the total volume of CO_2 stored as wood-based products, enlarging the life-cycle of the fixed carbon in the new recycled products.

Due to the continuing expand of urban land, the increasing expansion of urban forests is predictable. Taking into account reasons of safety, aesthetics and increasing environmental awareness the case of this study is found important for the future.

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8. PUBLICATIONS AND CONGRESSES

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*. VI Congreso Ibérico de AgroIngeniería. University of Evora, Portugal, 5-7 of Sept. 2011.

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Fernandez- Sarría A., Martínez L., Velázquez-Martí B., Sajdak M., Estornell J., Recio J.A., Hermosilla T. 2011. Diferentes metodologias de calculo de volumen de copa en *Platanus hispanica* empleado laser escaner terrestre. XIV Congreso de la Asociación Española de Teledetección. Mieres del Camino, Asturias, 21-23 Sept.

Sajdak M., Velazquez-Marti B. 2012. Estimation and comparison of pruned biomass depending on location and pruning practice applied in urban *Morus alba* trees. International Conference of Agricultural Engineering CIGR-Ageng2012, Valencia, Spain 8-11 July.

Sajdak M., Velázquez-Martí B. 2012. Estimation of pruned biomass through the adaptation of classic dendrometry on urban forests: case study of *Sophora japonica.* Renewable energy 47:188-193.

Other papers are being reviewed in several journals included in Journal Citation Report:

Velázquez-Martí B., Sajdak M., López-Cortés I., Fernández-Sarría A., Estornell J. Fernández-Sarría A., Estornell, J. 2012. Prediction models to estimate prunned biomass of *Platanus hispanica* to do raw material surveys from urban systems. Forest Science.

Velázquez-Martí B., Sajdak M., López-Cortés I. Available residual biomass obtained from pruning of Morus alba trees cultivated in urban forest. Renewable Energy.

Fernandez-Sarría A., Martínez L., Velázquez-Martí B., Sajdak M., Estornell J., Recio J.A. 2012. Different methodologies for calculating crown volume of Platanus hispanica trees by terrestial laser scanner and comparison with classical dendrometric measurements. Computers and Electronics in Agriculture.

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9. ANNEX

Table 82. Field data sheet 1

TEST DETERMINATION OF BIOMASS COMING FROM PRUNING OPERATIONS OF PALM TREES

GENERAL INFORMATION DATE

Species:	
Variety:	
Location:	Province:

Contact person		
Address		
Telephone		Mobile:
Email		

TREE MANAGEMENT INFORMATION

Biomass from pruning operations

Date of last pruning operations ______

Type of previous pruning operations______

Tree number	
Diameter at breast height (cm)	
Crown diameter (m)	
Distance from soil to the crown (m)	
Total tree height (m)	
Number of cut leaves	

Green leaves	Weight (kg)	Length (cm)	Dry leaves	Weight (kg)	Length (cm)
Leaf 1			Leaf 1		
Leaf 2			Leaf 2		
Leaf 3			Leaf 3		
Leaf 4			Leaf 4		
Leaf 5			Leaf 5		
Leaf 6			Leaf 6		
Leaf 7			Leaf 7		
Leaf 8			Leaf 8		
Leaf 9			Leaf 9		
Leaf 10			Leaf 10		
Average			Average		

Table 83. Field data sheet 2

TEST DETERMINATION OF BIOMASS COMING FROM PRUNING OPERATIONS

GENERAL INFORMATION DATE

Specie:	
Variety:	
Location:	Province:

Contact person		
Address		
Telephone		Mobile:
Email		

TREE MANAGEMENT INFORMATION

Biomass from pruning operations

Date of last pruning operations ______

Type of previous pruning operations______

Tree number	Tree 1	Tree 2	Tree 3	Tree 4	Tree 5
Diameter at breast height (cm)					
Crown diameter (m)					
Distance from soil to the crown (m)					
Total tree height (m)					
Weight 1 (kg)					
Weight 2 (kg)					
Weight 3 (kg)					
Weight 4 (kg)					
Weight 5 (kg)					
Weight 6 (kg)					
Weight 7 (kg)					
Weight 8 (kg)					
Weight 9 (kg)					
Weight 10 (kg)					
Average (kg)					

Table 84. Validation data

Species	New equation (25 sample trees)	Number of validation data (sample trees)	T-Student	P-Value
Morus alba street location	$B= 10.288 + 0.0256723 \cdot dbh^2 - 0.182728 \cdot dbh \cdot h - 3.18406 \cdot dc \cdot hc + 1.95276 \cdot h \cdot dc$	5	0.0148328	0.988529
Morus alba park location	$B = -1.8355 - 3.04043 \cdot dc \cdot h + 17.7895 \cdot dc \cdot hc + 1.87746 \cdot h^2 - 35.3771 \cdot hc^2$	5	0.862554	0.413491
Platanus hispanica	$B = 3.3003 - 0.500268 \cdot dc^2 + 0.270102 \cdot dc \cdot dbh$	5	-0.54426	0.601098
Sophora japonica	$B= 11.3625 - 0.871214 \cdot hc \cdot h +0.213012 \cdot hc \cdot dbh +0.168353 \cdot h^2 +0.0274955 \cdot hc \cdot h \cdot dc$	5	-0.414982	0.689061
Phoenix canariensis	$B = -483.752 + 145.266 \cdot dc - 36.1174 \cdot h + 56.9057 \cdot hc - 0.395022 \cdot dbh \cdot dc + 0.840297 \cdot dbh \cdot h - 0.896813 \cdot dbh \cdot hc -4.74705 dc^2 - 6.50947 \cdot dc \cdot h + 8.45532 \cdot h \cdot hc - 8.75568 \cdot hc^2$	5	-0.44431	0.668529
Phoenix dactilifera	$B = 64.4552 - 19.651 \cdot h + 20.2859 \cdot hc + 1.70061 h^2 - 2.08599 \cdot h \cdot hc$	5	0.391497	0.705651
Morus alba	$V = -591.746+ 507.093 \cdot do^2 - 2.09281 \cdot do^2 \cdot l + 0.0083961 \cdot do \cdot l^2$	5	-0.092665	0.928448
Morus alba	$B = 2.65673 + 0.573367 \cdot V cone$	5	-0.247364	0.810857
Morus alba	$B = 2.65673 + 0.382245 \cdot V paraboloid$	5	0.247367	0.810855
Platanus hispanica	$B = 6.10934 + 0.0992547 \cdot Vcone$	5	-0.694087	0.507279
Platanus hispanica	$B = 6.10934 + 0.0661698 \cdot Vparaboloid$	5	-0.694087	0.507279
Platanus hispanica	$V = -11.2731+ 0.620237 \cdot do^2 \cdot l$	5	0.0613361	0.952596
Sophora japonica	$V = 23.6538 + 0.313124 \cdot do^2 \cdot l$	5	0.068944	0.946726